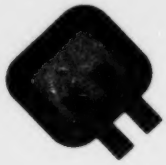

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# A PROPOSED ELECTROCHEMISTRY RESEARCH PLAN FOR THE CHEMICAL RESEARCH DEPARTMENT

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Report No 85-120-K

## ABSTRACT

A five-year electrochemistry research plan for the Chemical Research Department is proposed. Major programs, related to electrochemistry are discussed and their objectives are established. The need to develop new technologies for both utilizing and generating electricity is also discussed. High priority is assigned to processes with large load building potential such as the development of electroorganic synthesis processes and development of batteries for EV and utility application. Lower priority is given to the development of fuel cells for power generation and technologies with lower load building and/or market potential such as electrolyser technologies, electroleaching and deposition, pollution control and waste recycling.



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## EXECUTIVE SUMMARY

The implementation of existing and emerging electrochemical technologies in the transportation and industrial sectors offers numerous opportunities for increasing electricity utilization. As a result, electrochemical research activity in the US, Canada and Japan is increasing at a rapid pace. The major research effort in the US is being funded by various departments of the federal government, EPRI, the electric utilities and many industrial sectors. The Institute of Hydrogen Systems (IHS) in Ontario is heavily involved in electrochemical research specifically in areas related to hydrogen energy systems. Among Canadian electrical utilities, Hydro Quebec maintains the highest profile electrochemical group at IREQ. BC Hydro also maintains a visible electrochemistry group at its research laboratories. The Japanese Central Research Institute of Electric Power Industry (CRIEPI), government laboratories and several major companies are also heavily involved in the development of electrochemical technologies mainly for electricity generation and storage.

Prior to 1981 the Chemical Research Department's electrochemistry program was restricted to Supply Management related work such as: water-waste water treatment, corrosion and battery testing. In response to the Corporation's recent Demand Management Strategy, a more extensive electrochemical research program, which is described in this report, was initiated in 1981.

It is recommended that the effort expended on the electrochemistry research program be increased because of the opportunities that the development of various electrochemical technologies offer to Ontario Hydro and the Province in terms of increased electrical load and improved system operation. The overall objectives of this program are: to determine the viability of promising electrochemical technologies that offer opportunities for increasing the utilization of electrical energy (electrosynthesis and batteries) and energy conversion (fuel cells), and to assist in developing the most promising ones.



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Electrochemical Synthesis Program This work is aimed at the development of selected organic and inorganic processes that could be commercialized in Ontario thereby creating new industrial markets for electricity. It is proposed that the Research Division take a leading role in encouraging the chemical industry to explore the potential advantages of electrochemical synthetic routes.

A literature review (partly funded by CEA) is in progress to identify chemicals that could be economically produced using electrochemical methods. Promising processes identified in this literature study will be developed for bench scale demonstration. Results from the studies will be widely circulated to invite interest from the chemical industry and the Province of Ontario. It is anticipated that during the demonstration stage, enough outside interest can be generated for further scale-up and evaluations.

Battery Research Program The objective of this work is to develop, monitor developments elsewhere, and evaluate the performance of high performance batteries suitable for EV and utility applications in order to keep the Corporation informed of new opportunities as they emerge.

To meet these objectives it is necessary that we maintain in-house capabilities to conduct research programs and in-depth evaluation of technologies as they emerge.

In addition to periodic literature studies, in-house research projects that will allow closer interaction with various developers are proposed. It is recommended that the current polymer battery work be continued and expanded with additional staff to exploit the promising developments in new polymeric electroactive materials made in our laboratory. Prototype battery evaluation will continue at our battery test facility to assess the suitability of new technologies for electric vehicle and bulk energy storage applications.

Fuel Cells This work is aimed at (a) acquiring and maintaining the awareness of developments taking place elsewhere in order to alert others within the Corporation of opportunities, (b) gaining the ability to develop and exercise technological leadership within the Corporation, and (c) becoming an informed buyer in case of the Corporation's adoption of the fuel cell generation option.

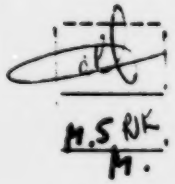
To meet these objectives, the latest developments in emerging fuel cell technologies will be closely monitored. Technical and economic viability of the most promising fuel cell power generation options will be assessed periodically. In 1988, when advanced fuel cell power plants are expected to become available it may be appropriate to install, test and evaluate the most promising one in Ontario Hydro's system.

Other Electrochemical Technologies and Consultation A minor effort is proposed to monitor major developments in other technologies such as electrolytic hydrogen generation, electrodeposition, photoelectrolysis and electrochemical waste treatment and recycling. There is an ongoing need to provide consulting services in very diverse areas of electrochemistry, therefore these services will be maintained.

Priorities, Program Cost, Schedule and Manpower Requirements Highest priority is assigned to the development of technologies with large load building potential such as electrochemical synthesis and batteries for EV application. Until about 1988 low priority is assigned to the development of fuel cell technology. Consultation and keeping abreast of the development of a variety of other electrochemical technologies are expected to be ongoing activities requiring relatively minor effort.

In 1985, three professionals and one technician would be required to carry out the proposed studies at an estimated cost of $370,000 ($1985). Manpower requirements and costs are expected to increase gradually as the projects expand with more extensive involvement in experimental programs. Estimated OM&A costs will peak in 1988 ($1,100,000) when a total of six professionals and seven technicians would be required. The additional staff being required for a field evaluation of an advanced prototype fuel cell power plant module.

Current resources are limited to one professional and one technician. It is obvious that if no more resources are available, only a very limited part of the program can be accomplished. The proposed electrochemistry R&D program warrants a long term commitment if the Corporation is to benefit from the implementation of these new technologies.



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To Mr. F.J. Kee
Director of Research

# A PROPOSED ELECTROCHEMISTRY RESEARCH PLAN FOR THE CHEMICAL RESEARCH DEPARTMENT

## 1. INTRODUCTION

As a result of the high cost of imported energy, excess generation capacity and strict environmental regulations, Ontario Hydro, like many large utilities in the US, is exploring new technologies for both utilizing and generating electricity more efficiently. Other compelling factors include environmental concerns and the uncertain economic climate for committing major capital outlays.

Now, and most likely into the early 1990's, the Corporation is emphasizing "Demand Management", ie, the increased utilization of electricity in Ontario. The objective of this strategy is to increase electricity's market share from 16% in 1980 to 20% in 1990. Discussions with the Market Planning Department suggest that the marketing of electricity is likely to continue beyond the 1990's/1/. The development of new markets for electricity is necessary in order to meet this objective.

Transportation and industrial sectors are the largest users of energy. Most of the energy used in the industrial sector is derived from fossil fuels (Fig 1). The transportation sector is responsible for 50% of the petroleum consumption on a national basis. These sectors, however, offer numerous opportunities for the displacement of fossil fuels by electricity through the implementation of existing and emerging electrochemical technologies.

On the generation front, uncertain economic environments, growth projections and environmental concerns necessitate a re-evaluation of high efficiency, modular generation options to allow latitude in construction and planning, to reduce financial burdens associated with building large generating stations and transmission facilities. Emerging fuel cell technologies show the promise of being a viable generation option.

The purpose of this document is to identify new electrochemical technologies that offer opportunities in the areas of utilization and generation of electricity. Potential benefits of these technologies to Ontario Hydro are identified and research programs have been suggested to (a) generate innovative ideas, and screen these ideas through bench and pilot scale testing and market promising concepts to those in a position to develop and commercialize products, (b) carry out assessments of prototype and commercial products, and (c) provide leadership by monitoring developments elsewhere and alerting others within Ontario Hydro to opportunities.

## 1.1 Electrochemistry and Electric Utilities

Electrochemical processes involve direct conversion of electrical energy to chemical energy or vice versa. The interest of electric utilities in electrochemistry and electrochemical technologies is not surprising. According to the US Department of Energy (DOE), about 15% of the electricity produced in the US is used in electrochemical processes/2,3/ which include electrochemical synthesis, winning and refining of metals and electroplating.

A number of new emerging electrochemical technologies will impact utilization and generation of electricity: development of the 'right battery' for electric vehicle and bulk energy storage would impact utility loads and the bulk electrical system operation; development and commercialization of electrochemical synthetic processes would add to the electric load; implementation of fuel cell technologies would allow coping with economic uncertainties of large generating facilities. The application of electrochemistry and electrochemical technologies in a number of other areas such as: hydrogen production, waste treatment, waste recycling, metal refining, etc, can also be envisioned. Electrochemical techniques may also play a major role in nuclear waste disposal and nuclear waste processing.

Electrochemical research activity in the US is brisk, being funded by Department of Energy (DOE), National Aeronautic and Space Administration (NASA), Department of Defence, Electric Power Research Institute (EPRI) and most sectors of industry including the electric and gas utilities and the chemical, oil and gas industries. In its multiyear planning DOE has proposed the establishment of a center of excellence in electrochemistry.

In Japan the Central Research Institute of Electric Power Industry (CRIEPI) and its member utilities, government laboratories and several major companies (Mitsubishi, Panasonic, Sanyo, Hitachi, Toshiba and Fuji) are involved in the development of electrochemical technologies for generation and storage of electricity. These companies are involved in a joint effort at an annual cost of about 100 million dollars to bring fuel cell technology to the domestic and foreign market as quickly as possible.

In Canada, the highest profile electrochemistry group is at IREQ where a strong group of 23 people is conducting generation and utilization related research programs. Their main focus is the

development of polymer electrolyte batteries. A minor program, on the evaluation of Electrolyser Corporation's electrolytic hydrogen generation pilot unit, has been underway for a couple of years. At present, IREQ is very aggressive in fuel cell testing and have purchased a 40 kW phosphoric acid fuel cell power plant from United Technologies for 1.3 million dollars. Out of the $4 million/year budget of the electrochemistry department, $3.8 million is internally funded.

Recently, Hydro Quebec decided to establish another electrochemical research institute under the name "Electrochemical Technologies" Laboratory in Shawinigan. The new laboratory will have close connections with IREQ and will employ 50 people. According to Dr. G. Belanger, Manager, Electrochemistry Department at IREQ, this new laboratory is being set up as part of a long term strategy that aims at attracting electrochemical industry into Quebec.

BC Hydro maintains a visible electrochemistry group of six people involved in fuel cell evaluations, electrosynthesis and related projects.

In Ontario, the Institute of Hydrogen Systems is involved in the development and application of hydrogen based electrotechnologies. The major projects are aimed at the development of specific hydrogen fuel cells, water electrolyser and batteries.

The Canadian Electrical Association (CEA) has recently also initiated a number of electrochemical research programs related to fuel cells and electrochemical synthesis.

### 1.2 Electrochemistry Research at OHRD

Prior to 1981 the Chemical Research Department was involved in a number of studies related to electrochemistry. These studies, mainly in support of Supply Management programs, included:

- development of water and waste water treatment processes;
- application of electrochemistry in corrosion research; and
- evaluation of prototype batteries at the battery test facility.

In response to the Corporation's Demand Management strategy, an electrotechnology R&D program was initiated in 1981 with a broad objective to develop innovative electrochemical technologies in order to improve utilization of electricity in the Province as a substitute to fossil fuels. Three main areas of electrochemical applications were identified: energy conversion, energy storage and chemical processing.

After an initial period of selecting, ordering and setting up the electrochemistry laboratory, the program was initiated with literature reviews on fuel cell development and applications/4/

and on water electrolysis for hydrogen production/5/. The reviews identified areas where R&D work is needed for improving the performance and economics of these new technologies.

Following these recommendations, a research project was initiated on the development of low cost NiO based catalysts aimed at improving the performance of alkaline water electrolysers. Since June 1983, a modest research effort has been in progress on the development of advanced secondary batteries for propulsion of electric vehicles and utility load levelling.

Since December, 1984, a literature study, partly funded by the Canadian Electrical Association (CEA), has been in progress to identify medium to large tonnage chemicals (>1000 tons/year) that could be economically produced using electrochemical methods. Dr. N. Weinberg of Electrosynthesis Co., Buffalo and Dr. B. Fleet of EMC Ltd, Toronto, are collaborating with us in this study.

Because of the potential energy merits, economic competitiveness, environmental acceptability of electrochemical processes and the increased load demand that could result from the commercial application of these technologies, we are proposing to expand the Department's electrochemistry related programs to develop, monitor, and evaluate some of the most promising technologies.

## 2. OPPORTUNITIES FOR UTILIZATION OF ELECTRICITY

New markets for electricity can be identified in all sectors of the economy but not all sectors are expected to benefit equally from the emerging technologies. New markets for electricity in the residential and commercial sectors deal mainly with space conditioning applications and the technology needed for these is already developed. Some advancement in these technologies can be expected, but this will not affect the market potential significantly. Most of the incremental opportunities in the residential sector will be harvested during the next five years. The opportunities during the 5 to 20 year period are expected to be limited.

Opportunities in the agricultural sector generally involve refinements of existing technologies (eg, heat pumping, radiant heating). Use of steam from generating stations for greenhouse heating is an alternative energy opportunity that has yet to be fully exploited, though little appears needed in terms of new technology.

Major opportunities exist for increased electrical use in the industrial and transportation sectors which are now heavily dependent on fossil fuels to provide energy requirements. Different emerging electrochemical technologies impacting these sectors are discussed briefly in the following sections.

## 2.1 Industrial Sector

Ontario's industrial sector is a major user of energy but at present only about 20% of the energy it uses is electricity; the main part is derived from fossil fuel (Fig 1). Energy in the industrial sector is used mainly in manufacturing and is concentrated in a few industries such as: pulp and paper, chemicals, iron and steel, metal smelting and refining, cement and petroleum refining. Electricity is capable of providing an increased share of industrial energy through the implementation of existing and emerging electrochemical technologies.

The following electrochemical technologies could be used more extensively in the industrial sector creating varying amounts of load during the next 5 to 20 years:

- Electrochemical synthesis of organic and inorganic chemicals.
- Cathodic processes for the recovery of metals from industrial effluents.
- Anodic destruction processes such as cyanide or organic destruction.
- Water electrolysis.
- Electrochemical waste recycling - selective recovery of metals.
- Electrolytic production of metal powders.
- Electrodissolution of ores coupled with electrodeposition in mining.
- New electrowinning and refining processes.
- Electrodialysis.
- Electroflotation for electroconcentration of solids.

The large scale use of electricity in the electrochemical industry today is dominated by extractive metallurgy, metal refining and the chloralkali industry.

In terms of energy usage, the aluminum industry is by far the largest user, with chloralkali second. Water electrolysis could be significant in a "hydrogen economy". Electrowinning and refining of metals will continue to grow. But the largest growth may be predicted for electrosynthesis of organics since it offers opportunities for producing chemicals more efficiently with greater selectivity and in an environmentally more acceptable manner than conventional means of production.

### 2.1.1 Electrosynthesis

Electrochemical synthetic processes involve direct conversion of electrical energy to chemical energy. Although most chemicals are manufactured using well established technologies that need fossil resources, major opportunities exist for increased electricity use in electrochemical synthesis of new chemicals. In light of lower costs for electric power, easy access to US markets and proposed tarrif free trade currently being discussed between the US and Canada, electrochemical synthesis offers an exceptional opportunity to Ontario Hydro and the Province of Ontario.

Electrochemical synthesis consumes a considerable quantity of electricity even today. Most chemicals produced electrochemically in the US and Canada are inorganic chemicals, related to the chloralkali industry, such as: chlorine, caustic, hypochlorite, chlorate, perchlorate, etc. Only a few new electroinorganic processes can be envisioned such as electrolytic production of ozone, which may increase electric consumption over a 10 to 20 year time frame. It seems likely that electricity utilization with the existing electroinorganic processes will decline with continuing research to improve the energy efficiency.

Electroorganic processes offer the greatest opportunities. Of the 18 commercial processes worldwide only two are being used in the US. About 40 more processes are at different stages of pilot scale development. If the number of publications and the research activity is some indicator, it appears likely that this number will increase further.

Electroorganic synthesis has a well established scientific base, the nucleus for growth in commercialization. It has a number of potential economic, environmental and energy use benefits. Electroorganic processes are inherently energy efficient, product selective, clean, compact and pollution free. In fact, there are several reactions, such as fluorocarbon synthesis, for which electrosynthesis is the only practical approach. In certain cases the electrochemical route allows the use of different starting materials.

Electrochemical synthesis of tens of thousands of organic compounds has already been demonstrated in microscale in organic polarography and voltammetry. Of these only about 18 have been used at commercial levels in different countries including the US, Japan, Germany and India. The reasons for this slow progress are both economic and technical in nature. Identification of chemicals that can be synthesized electrochemically and have high enough demand has been slow because of the complexity of electrochemical reactions and the lack of incentives to develop new processes to compete with already existing conventional synthetic processes. In the past, unavailability of suitable cell components and the lack of knowledge of electrochemical

engineering for scaling up have also contributed to the slow progress.

The situation has become more favourable during the last decade with the rapid rise in the cost of fossil fuels and increasing environmental concerns. A number of technological developments have also occurred which make commercialization of electroorganic processes more feasible today than in the past. These developments include:

- Advances in the field of electrocatalysis.
- Advances in membrane technology.
- Advances in electrochemical engineering, electrode and reactor design.
- Availability of new analytical tools to study reaction mechanisms.
- Rapid success of Monsanto Adiponitrile process and scale-up experience gained therein.
- Experience gained in developing approximately 60 electroorganic processes, 18 of which are already commercial worldwide.

It is a widely accepted view that new large tonnage organic chemicals produced via an electroorganic process can be identified. However, the identification of small or medium tonnage chemicals appears to be equally important because:

- The economic incentives for the development and commercialization of synthetic processes for small tonnage high-priced chemicals could be large enough to justify the investment.
- Experience and knowledge gained during the development and commercialization of those processes could be directly applicable to most large tonnage processes.
- The total load of a number of small tonnage processes may be the same as that of a single large tonnage process.

Most studies funded by DOE and EPRI, in the past, have been aimed at evaluating large tonnage processes. The scope of these studies has been narrow as they tended to evaluate state-of-the-art processes rather than identify new electrochemical processes (Table I). A weakness of these studies is indicated by the ethylene glycol example. In a 1979 study ethylene glycol could not even be listed as a process with promise because of the selection guidelines set out. Four years later, it has the promise of becoming the largest electroorganic process. The authors believe that by conducting a broader study with relaxed selection rules new large tonnage processes can be identified. Such a study, partly funded by CEA, is in progress in our laboratory aimed at identifying medium or large tonnage chemicals that could be economically produced electrochemically.

A brief description of this technology is given in Appendix A. Due to the potential advantages of electroorganic processes for Ontario Hydro, a research program is proposed in Section 4.1.

## 2.2 Transportation Sector

Transportation is the single largest user of fossil fuels. The use of electric trains, trams and buses will undoubtedly grow in the future and take care of local mass transit and possibly some intercity transit systems operating along fixed routes. Other modes of transportation requiring greater mobility, such as personal transportation would require energy storage. Battery and fuel cell powered electrical vehicles are actively being developed around the world. Both routes may impact utility loads during the next 10-20 years.

### 2.2.1 Battery Powered Electric Vehicles (EVs)

Electric vehicles have the highest potential for petroleum substitution. They are quieter, less polluting and mechanically simpler than the transport driven by diesel or gasoline engines. They could conserve oil and use power stations more efficiently with overnight charging of their batteries. It is for this reason that electric utilities have been promoting the development of electric vehicles since the beginning of this century.

Despite the fact that an electric car held the world land speed record in 1899 at 105 km/h, electric vehicles have not found commercial acceptance. This is attributed to the unavailability of the right kind of battery.

It has been the consensus that the lead-acid battery is the only battery well enough developed for application in electrical vehicles. The energy density of the lead acid battery is very low for a practical vehicle. For example, a small family car travelling 100 km might require 10 kWh of energy which would be supplied by, say, 10 litres of gasoline. A 400-kg battery occupying 25 times the space of gasoline would be required to drive the car an equal distance.

A number of new primary and secondary battery systems are being developed around the world. Some of these batteries show the promise of being used in all electric vehicles or electric hybrid vehicles. Which battery finds ultimate acceptance remains to be seen but there appears to be significant optimism that by the year 2000 needed developments would have occurred so that about 6% of the vehicles could be electric vehicles.

Electric utilities are interested in the development of batteries for EVs since their widespread use could not only significantly increase load demand but could also enable a more efficient use of existing electric generating capacity through off-peak EV battery recharging that uses economic base load power.

As discussed later, storage batteries potentially offer compact, quiet and non-polluting systems for load levelling, peak shaving and for providing spinning reserve. A recent study at Battery Energy Storage Test Facility (BEST) has concluded that state-of-the-art batteries and power conditioning equipment is suitable for these applications.

In light of the importance of batteries to utilities, a research program is proposed in Section 4.2. A brief overview of battery technology is given in Appendix B.

### 2.2.2 Fuel Cells for Electric Vehicles

Fuel cells, using electrolytic hydrogen as the fuel, offer an alternative power source for electric vehicles. Hydrogen from reformed hydrocarbons would compete with electrolytic hydrogen in the near term, due to difficulties of onboard hydrogen storage. Hydrogen storage in the form of ammonia and hydrazine has been proposed along with other modes of hydrogen storage such as liquid, pressurized hydrogen and metal hydride. Whichever route is chosen, fuel cell powered EVs will impact utilities' electrical loads.

A fuel cell suitable for this application should have short starting time, easy start even at subzero temperatures, high power density, easy fuel handling and storage and abundant availability of low cost fuel. Of all the fuel cells, alkaline fuel cells (that require pure electrolytic hydrogen) appear to be most suitable for this application. The use of phosphoric acid fuel cells as well as solid polymer electrolyte (SPE) fuel cells is also being evaluated for this application. These fuel cells can operate on reformed hydrocarbons and methanol. The reformation has to be carried out onboard with a reformer.

For fuel cells to be practical for electrical vehicles, the power density must be increased by a factor of two to three times that of average levels in older systems (peak power 2-4 $kW/ft^3$). This improvement could be achieved either through increased refinements to reduce cell thickness and weight. Higher current density operation of fuel cells has been shown to be possible in the laboratory. With existing technologies, the high energy density of fuel cells may be exploited in fuel cell-battery hybrid vehicles.

Practically all fuel cell technologies suitable for electric vehicle applications require platinum catalysts. Significant developments, however, are taking place that could reduce the catalyst cost and improve power density.

In Canada, alkaline fuel cells employing electrolytic hydrogen as fuel appear to be ideal for transportation applications. In light of a major effort in this direction at the Institute of Hydrogen Systems (IHS), no research program is proposed. Close cooperation with IHS and a periodic review of fuel cell

technologies is recommended as described in generation related programs (Section 4.3).

## 3. GENERATION AND STORAGE OPTIONS

As a result of the difficulties Ontario Hydro is facing in obtaining approval for transmission facilities, opposition to very large central generating stations with their large capital costs, long lead times, etc, there is considerable interest within the Corporation in evaluating and considering high efficiency, shorter lead time and environmentally acceptable modular means of generating electricity.

Storage options are necessary to utilize the existing generation facilities effectively. Load leveling, peak shaving and spinning reserve capabilities are required by utilities as well as large utility customers.

Electrochemical technologies (fuel cells and batteries), offer alternatives for generation and storage applications. They are being evaluated in the US and Japan.

### 3.1 Fuel Cells for Power Generation

Fuel cell power plants could indeed become a very attractive power generation option since they are very efficient, environmentally benign and, due to their modular character require short construction lead times. They could be sited almost anywhere thereby reducing the cost of transmission facilities. New generation fuel cells may find applications in base load generation and industrial cogeneration.

Commercialization of fuel cell technology is gaining momentum, especially in the USA. The 4.5 megawatt phosphoric acid fuel cell demonstration power plant (PAFC) built by United Technology Corporation (UTC) for Consolidated Edison in New York City has been held back by repeated difficulties. In contrast an identical sister plant, designed by UTC for Tokyo Electric Power Co (TEPCO) has operated flawlessly and to date has logged hundreds of hours of peak power/8/. Both plants operate on naptha or natural gas. UTC's strategy now is to upgrade its present PAFC power plant so that it delivers 11 megawatts of power. UTC will have several of these larger units ready for delivery by 1987.

Furthermore, UTC is delivering almost 50 units of lower power (40 kW) to the Department of Energy (USA) to undergo a full scale testing program. These units will operate on natural gas. Besides the DOE, some units have been sold to Canada (2), Mexico and Japan. The Canadian units are being operated by BC Hydro and IREQ. The fuel cell power stack of these units is of the same design as the one considered for the multimegawatt systems. It integrates all the new features of these large units, especially the electrolyte (phosphoric acid) retention system. UTC faces competition from Westinghouse; which has recently signed a

contract with Southern California Edison to build a prototype 7.5-megawatt air-cooled phosphoric acid power plant scheduled for initial operation in 1988. General Electric had been focussing on molten carbonate ("second generation") fuel cell technology, whose commercial development is thought to be lagging about seven years behind phosphoric acid cells.

There is a great interest in the USA for this energy conversion device as manifested by the active participation of the electric utilities in the Fuel Cell Users Group of the Electric Utility Industry. This group monitors and orients the work of the developers, UTC, Westinghouse, and General Electric so that the fuel cell power plant (FCPP) will be suited for industry needs.

CEA has recently initiated its own program aimed at keeping the Canadian electric utilities abreast of the development of this new generation technology and to get first-hand data on the latest technological improvements.

In an era where the low electric load growth restricts large scale projects, the availability of fuel cells, with multifuel capability, short lead time, small incremental power addition to networks (11 MW and multiples thereof) and the possibility of siting them near the load, make these units unique for the present electrical market situation.

In light of these possible applications of fuel cell technology, it is prudent that Ontario Hydro Research Division be closely monitoring the developments in this technology. An overview of the present state of knowledge of this technology is given in Appendix C. A modest research program is proposed in Section 4.3.

## 3.2 Secondary Batteries as Storage Options

Secondary batteries have been given much consideration for application to load levelling for electric utilities. Some of their advantages as a bulk energy storage device include:

- mitigation of oil shortage and import problems;
- uniquely versatile and rapid response to electric system needs;
- valuable for system regulation;
- battery output can exactly match incremental changes in load without efficiency penalty;
- modular construction for easy installation and lower capital cost;
- shorter lead time for construction;
- few, if any, site restrictions;

- potential savings in transmission costs;

- increased reliability resulting from modularity; and

- virtually free of environmental problems such as pollutants, heat dissipation and noise.

The major drawback of current batteries is that they do not meet required performance, life and cost standards. Most of the battery technologies being developed for EVs would also be suitable for bulk storage.

## 4. PROPOSED R&D PROGRAMS FOR 1985-1989

The overall objective of the electrochemistry research program is to help Ontario Hydro determine the viability of promising electrochemical technologies that offer opportunities for increasing the utilization of electrical energy and for energy conversion and to assist in developing the most promising ones.

The proposed programs related to the utilization of electrical energy in the industrial and transportation sector respectively include:

- electrosynthesis and batteries, and

- energy conversion: fuel cells.

To accomplish these objectives it is recommended that research programs be initiated in these areas aimed at providing leadership to the Corporation by (a) generating and developing innovative ideas through bench and pilot scale testing and marketing promising concepts to those in positions to develop and commercialize products, (b) testing and assessing prototypes and commercial products, and (c) monitoring developments elsewhere. Objectives, strategies and specific research activities in each subprogram area are given along with their estimated schedule, manpower requirements and costs.

### 4.1 Electrosynthesis

The objective of the electrosynthesis program is to develop selected organic and inorganic processes that can be commercialized in Ontario. Successful development of such processes could create new industrial markets for electricity. In order to achieve this objective OHRD would take a leading role in encouraging the chemical industry to explore the potential advantages of promising electrochemical synthetic routes. The following research projects would be undertaken, the schedule and costs of which are shown in Table II.

(a) Literature Review

A literature review is in progress to identify large and medium tonnage (ranging between 10,000 to 1,000 tons/year) organic and inorganic chemicals that could be economically produced using electrochemical methods. This is a two phase project consisting of a review of existing industrial electrochemical processes and an assessment of specific chemical candidates for an expansion of this market. In addition to electrosynthesis literature, fundamental polarographic and voltammetric data will also be used to make a creative contribution to the field. Based on these data, chemicals with the most favourable market potential will be selected for development. The results will be widely circulated to invite interest from chemical industry and the Province of Ontario. This study is cofunded by the Canadian Electrical Association.

(b) Development and Demonstration of Electrosynthetic Processes

Promising processes, identified in program (a) will be developed for demonstration at the bench scale. Specific tasks of this project would include: electrochemical cell design, demonstration of the technical feasibility of selected process or processes on the bench scale, and optimization of process parameters for maximum product yield. Economic feasibility of the processes will be assessed and recommendations for further scale up will be made.

It is anticipated that during this project enough interest will be generated from outside for further scale up, evaluation and demonstration of the most promising electrosynthetic processes.

4.2 Batteries

The objective of the battery research program is to develop, monitor the development elsewhere and evaluate the performance of high performance batteries suitable for EV and utility applications.

While it is understood that the development and commercialization of the "right type of battery" for EV and bulk energy storage applications would be spearheaded by the battery manufacturing industry, it is in Ontario Hydro's interest to contribute to and promote these developments, keep up to date with the battery development and keep the Corporation informed of new opportunities as they emerge. Such a program will ensure our scientific contribution to the development of "right type of battery" and keeping up with the latest developments. Costs and schedule of the program are summarized in Table II.

(a) Literature Surveys

Periodic critical literature studies will be conducted to identify and evaluate emerging new battery technologies. Our

own battery research programs described below will aid in these studies as they will allow closer interaction with developers.

(b) Polymer Battery

An in-house research program initiated in 1983 is in progress aimed at the development of polymer batteries. The first phase of the program, the development and characterization of novel stable conducting polymers capable of retaining higher charge levels than conventional ones, such as polyacetylene and poly-p-phenylene is complete. Based on the results to date novel heterocyclic polymers HP021, HP023, or HP024 appear to be the most promising positive electrode materials in a polymer battery. These polymers appear to be stable, and can be p-doped to yield maximum open circuit potential of 4.2V versus Li reference electrode. Doping levels of approximately 20% have been achieved on a micro-electrode, and they show good charge/discharge behaviour.

In the second phase of the program one $cm^2$ single cells using HP024, HP023 and HP021 will be fabricated to determine performance characteristics, such as energy and power density, energy efficiency, coulombic efficiency during repeated charge/discharge, shelf life, cycle life, etc. Depending upon the success of this program, multiple cell stacks using 10 $cm^2$ positive polymer electrodes will be designed, constructed and their performance characteristics evaluated.

(c) Prototype Battery Evaluation

Performance characteristics of advanced prototype batteries, as they become available, will be evaluated at the Battery Test Facility to assess their suitability for electric vehicle and bulk energy storage applications in the Canadian environment.

4.3 Fuel Cells

The objectives of the fuel cell program are to (a) acquire and maintain awareness of developments taking place elsewhere in order to alert others within Ontario Hydro of opportunities, (b) to develop and exercise technological leadership within Ontario Hydro, and (c) become an informed buyer in case of adoption of fuel cell generation option by the Corporation.

To achieve these objectives a periodic review of state-of-the-art technology and evaluation of the technical and economic feasibility of the most promising fuel cell generation options is proposed. Later, when advanced second generation pilot scale fuel cells will become available, it is proposed to install, test and evaluate the performance of the most promising one at Ontario Hydro's system. Field testing is necessary to gain credible information on the potential application of Fuel Cell Power Plants (FCPPs) on actual utility systems in terms of economic viability, capacity need and operating modes and to foster a

better understanding of factors important to system planning with FCPPs.

(a) Technical and Economic Assessments of the Technology

To keep abreast of the latest developments in fuel cell technology, yearly technology review updates will be conducted. Advances will be closely monitored by active participation in the Fuel Cell User's Group and CEA fuel cell programs. Seminars and conferences related to fuel cell development will be attended and technical and economic viability and the applicability of the most promising fuel cells to Ontario Hydro's system will be assessed.

(b) Field Testing of Prototype Fuel Cell Power Plants

Although hands-on experience on an FCPP installed at a Canadian utility system could lead to a better understanding of factors important to system planning, the purchase of such a unit by OHRD for testing at this stage is perhaps not justified because of high capital costs (1.3 million dollars) and manpower requirements (approximately four manyears). Moreover, the performance data generated during this test program will not be significantly different from that generated by 50 other organizations involved in the testing of 40 kW phosphoric acid fuel cell pilot plants. It is recommended that arrangements should be made so that OHRD personnel can participate in one of the test programs (for example, at IREQ). Establishment of the Canadian equivalent of the Fuel Cell Users Group could provide another opportunity of sharing the cost with other utilities.

An option to purchase and evaluate an advanced pilot plant FCPP should be kept open until around 1988 when they are expected to be available.

## 4.4 Other Electrochemical Technologies and Consultation Services

Other electrochemical technologies that may impact utilities in the future include: electrolytic hydrogen production and its use in chemical synthesis, new processes for electrochemical leaching of ores and electrodeposition, electrochemical waste recycling, electrochemical treatment of industrial and domestic wastes, photoelectrolysis, etc. Although some of these technologies are already available commercially, their impact may not be sizeable during the next 5 to 10 years and maybe beyond. However, it is necessary for a utility to monitor these technologies for any major developments. In fact, some of these may find application in utilities' normal operation. For example, the vapour phase electrolyser is considered a likely candidate for the decomposition of highly tritiated water and electrochemical pollution control technologies may find application in regeneration of boiler cleaning solvents.

A minor effort is proposed to monitor major developments in these technologies by brief literature studies, attendance at related conferences and interaction with developers. A few professional manmonths every other year are required to follow up the development of these technologies and evaluate their potential impact on Ontario Hydro. No dedicated manpower is requested at this stage and the work will be conducted by professionals involved in other major program areas.

Ongoing consultation services are also provided for other branches in areas related to electrochemical technology. About two professional manmonths/year are devoted to consultation.

## 5. PRIORITIES, PROGRAM COST AND MANPOWER REQUIREMENTS

The schedule and estimated cost of the five-year electrochemistry research program is summarized in Table II. Highest priority is assigned to the development of technologies with large load building potential such as electrochemical synthesis and batteries for EV application. Due to limited resources until about 1988, low priority is given to the development of fuel cell technology. From 1985 to 1988 our involvement in this program will be limited to monitoring the technology development elsewhere. Our active involvement in the fuel cell program - testing and evaluation of advanced pilot scale fuel cell modules installed on Ontario Hydro's power grid - is postponed to 1988 when advanced fuel cell pilot plant modules are likely to become available.

Consultation and keeping abreast of the development of a variety of other electrochemical technologies is expected to be an ongoing activity requiring about four manmonths/year.

With current resources limited to one professional and one technician, only a very small part of the proposed program can be carried out such as reviewing the status of development of electrosynthesis and minor experimental work on the development of conducting polymers.

It is necessary to make a long-term commitment to the proposed electrochemistry R&D program if Ontario Hydro wants to make a significant contribution to the development of electrochemical technologies and to benefit from its implementation in the Province.

TABLE 11

SUMMARY OF ELECTROCHEMISTRY R&D PROGRAM
SCHEDULE AND COST

| Area/Program | 1985 | | 1986 | | 1987 | | 1988 | | 1989 | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. ELECTROSYNTHESIS | | | | | | | | | | |
| a) Literature reviews | ——— | | | | | | | | | |
| b) Development and demonstration at bench and pilot scale | ——— | ——— | | | | | | | | |
| Manpower Requirements, manmonths | Prof 12 | Tech | Prof 20 | Tech 24 | Prof 22 | Tech 24 | Prof 24 | Tech 24 | Prof 22 | Tech 24 |
| 2. BATTERIES | | | | | | | | | | |
| a) State-of-the-art reviews | ——— | | | | ——— | | | | | |
| b) Development and evaluation of polymer batteries | ——— | ——— | | | | | | | ——— | |
| c) Evaluation of prototypes of advanced batteries | | | ——— | ——— | ——— | ——— | ——— | ——— | ——— | ——— |
| Manpower Requirements, manmonths | Prof 18 | Tech 12 | Prof 22 | Tech 24 | Prof 20 | Tech 24 | Prof 22 | Tech 36 | Prof 20 | Tech 36 |
| 3. FUEL CELLS | | | | | | | | | | |
| a) Technical and economic evaluations | | | ——— | | | | ——— | | | |
| b) Field testing of advanced fuel cell power plants | | | | | | | ——— | ——— | ——— | ——— |
| Manpower Requirements, manmonths | Prof | Tech | Prof 4 | Tech | Prof | Tech | Prof 24 | Tech 24 | Prof 24 | Tech 24 |
| 4. OTHER ELECTROCHEMICAL TECHNOLOGIES | | | | | | | | | | |
| a) Monitoring of developments in hydrogen, electroleaching/ electrodeposition, pollution control, waste recycling, etc. Also provide consulting services to other units. | ——— | | | | ——— | | | | ——— | |
| Manpower Requirements, manmonths | Prof 4 | Tech | Prof | Tech | Prof 4 | Tech | Prof | Tech | Prof 4 | Tech |
| 5. CONSULTATION | Prof 2 | Tech | Prof 2 | Tech | Prof 2 | Tech | Prof 2 | Tech | Prof 2 | Tech |
| Total Manpower Requirements, manmonths | Prof 36 | Tech 12 | Prof 48 | Tech 48 | Prof 48 | Tech 48 | Prof 72 | Tech 84 | Prof 72 | Tech 84 |
| Total Cost (Labour + M&A) $ x 1000 (1985) | $370 | | $650 | | $650 | | $1,100 | | $1,100 | |
| Capital Equipment $ x 1000 (1985) | | | $25 | | $25 | | $1,000 | | $25 | |

Note

The appendices are not meant to assess the state-of-the-art of the various technologies but rather are aimed at orienting the reader by giving a brief overview of the technology, assessing its potential for commercial application and identifying some areas requiring further development.

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# APPENDIX A

# ELECTROORGANIC SYNTHESIS

M.S. Mozes

ABSTRACT

Because of the potential energy merits, economic competitiveness and the increased load demand that could result from the commercial application of this technology, the development of selected electroorganic processes by the Chemical Research Department is proposed. The nature of electroorganic reactions is discussed and the types of reactions which can be carried out very favourably electrochemically are given. The economic aspects of these reactions and areas which need further development are briefly described. A five-year plan to develop selected electroorganic synthetic processes, its cost and schedule are given.

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## APPENDIX A

## ELECTROORGANIC SYNTHESIS

### 1. Introduction

Historically electrochemical processes have been limited to the manufacture of inorganic compounds. Indeed the production of chlorine and caustic alone amounts to approximately 2% of the total US consumption of electricity or about 5% of the electricity used by industry/1/. In Table 1A a summary of the production of electrochemicals in the USA is shown.

Commercial electroorganic processes have not found wide application mainly because electroorganic reaction behaviour is not yet fully understood. With the growing importance of energy, feedstock and environmental problems, there is now a widespread interest in the commercial potential of electroorganic synthesis.

Electroorganic synthesis offers opportunities for performing many reactions at controlled rates and with greater product selectivity than conventional means.

Some of the potential advantages of electroorganic synthesis over a conventional catalytic route are given below/2/. An electroorganic step may:

- permit elimination of one or more chemical steps;
- permit the use of alternative feedstocks;
- replace a hazardous step with no loss of efficiency;
- be environmentally benign;
- be energy efficient because it is performed at low temperature;
- require less maintenance because of the simplicity of the processes;
- require less manpower and other operating cost because of the high degree of automation that can be achieved.

Because of these advantages, it is likely that electroorganic synthesis will play a significant role in commercial processes in the near future.

### 2. The Nature of Electroorganic Reactions

Electroorganic synthesis involves the connection of two electrodes to a source of controlled potential, placing the electrodes in contact with a solution of reactants in a cell and passing an electric current from one electrode to the other. The cathode serves as a source of electrons while the anode acts as an electron sink. The electrons provided to the system serve as a reagent in the conversion of reactants to products. This is illustrated in Figure 1A, in the electroorganic oxidation of benzene to quinone, where an anolyte dispersion of

TABLE 1A

UNITED STATES PRODUCTION OF ELECTROCHEMICALS
KILOTONS (SHORT) PER YEAR (1)
(ESTIMATES IN PARENTHESES)

| | 1970 | 1980 | |
|---|---|---|---|
| Aluminum | 3,980 | 5,100 | • |
| Chlorine | 9,764 | 12,500 | • |
| Magnesium | (115) | 166 | • |
| Sodium | 171 | (190) | • |
| Sodium Chlorate | 198 | 250 | • |
| Zinc (Electrolytic) | (371) | | |
| Copper (Electrolytic) | (2,100) | 2,016 | |

---

o Uses reactant carbon anode, 0.45 lb C/lb Al (0.37 lb C/lb Al theor. at 90% C.E.)

• Use "inert" anode; for chlorine ~0.003 lb C/lb $Cl_2$ (theoretical zero consumption)

Dow process for magnesium uses ~0.1 lb C/lb Mg.

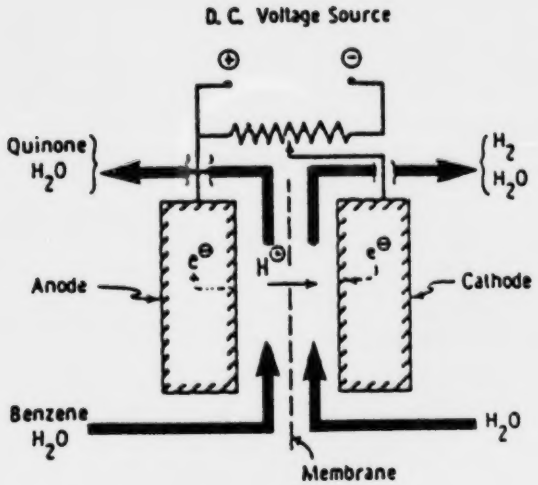



FIGURE 1A
ELECTRO-ORGANIC SYNTHESIS /3/

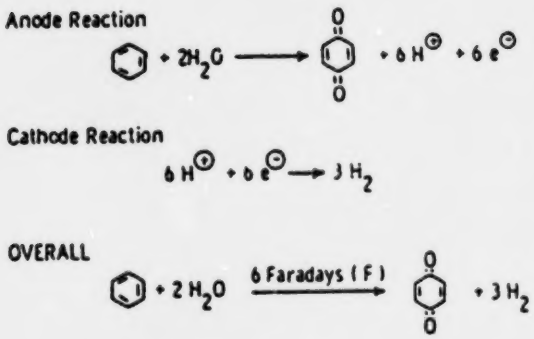

Anode Reaction
$+ 2H_2O \longrightarrow + 6H^{\oplus} + 6e^{\ominus}$
Cathode Reaction
$6H^{\oplus} + 6e^{\ominus} \longrightarrow 3H_2$
OVERALL
$+ 2H_2O \xrightarrow{6\ \text{Faradays (F)}} + 3H_2$

FIGURE 2A
SUMMARY OF ELECTRODE REACTIONS /3/

benzene in water is flowing through the anode compartment where benzene donates electrons to the anode yielding quinone. The complementary cathode reaction is the evolution of hydrogen. The electrode reactions are given in Figure 2A.

The reaction variables in electrochemical processes are complex and still poorly understood. The commercial size scale up of electrochemical processes is generally more difficult than that of a usual chemical process. Whereas chemical engineering is a well developed discipline, electrochemical engineering is still a relatively new field. The past two decades have witnessed significant advances in modelling of electrochemical systems but therein lies the difficult task. We must still rely heavily on direct scale up experience. Significant advances in associated fields such as energy storage and conversion, electroplating, and chloralkali production have contributed much to the better understanding of electroorganic processes.

The most important variables in determining the overall performance of an electroorganic reaction are summarized in Table 2A. Those variables which must be considered for an electrochemical reaction include the chemical as well as the electrochemical variables.

The electrode potential controls the rate of flow of electrons and hence the rate of reaction. Among the least understood of the electrochemical variables are the roles of the electrode material, electric field and adsorption. At modest electrode potentials, driving forces of many Kcal/mole can be attained resulting in the formation of very reactive species, such as free radicals, radical cations and anions, carbonium ions and carbanions can be generated. This is illustrated in Figure 3A, which shows energy levels as a function of applied electrode potential and the corresponding intermediates formed.

3. Electroorganic Reaction Types

There is a wide variety of possible electroorganic reactions. In Figure 4A a few reaction types which can be efficiently carried out electrochemically are given/1,3/. In Table 3A some practical electroorganic reactions are listed/4/.

4. Commercial Applications

There are a few successful examples of commercial applications for some of the electroorganic reaction types (Figure 5A).

- Monsanto Co has been operating a multi-million kg/y plant for manufacturing adiponitrile from acrylonitrile since the early 1960's. Asatic in Japan is also commercializing a similar ADN process.

- Nalco started a commercial process in the mid-1960's for manufacturing tetraethyl and tetrametnyl lead.

A number of commercial scale electroorganic syntheses are now under development.

- Bayer and Kellog have been developing propylene oxide from propylene and water.

TABLE 2A

VARIABLES TO CONSIDER IN ELECTROCHEMICAL REACTIONS

Usual Variables

We are normally concerned with these variables in chemical reactions

Concentrations of:

(1) Solvent/supporting electrolyte
(2) Substrate
(3) Other components:

Temperature
Pressure
pH
Time

Electrochemical Variables

An electrochemical reaction requires knowledge of both the usual and the electrochemical variables

Electrode potential
Electrode material
Current density
Electric field
Adsorption
Cell design
  (1) Compartmented
  (2) Membrane or porous separator
  (3) Static or flow cell
Solution conductivity

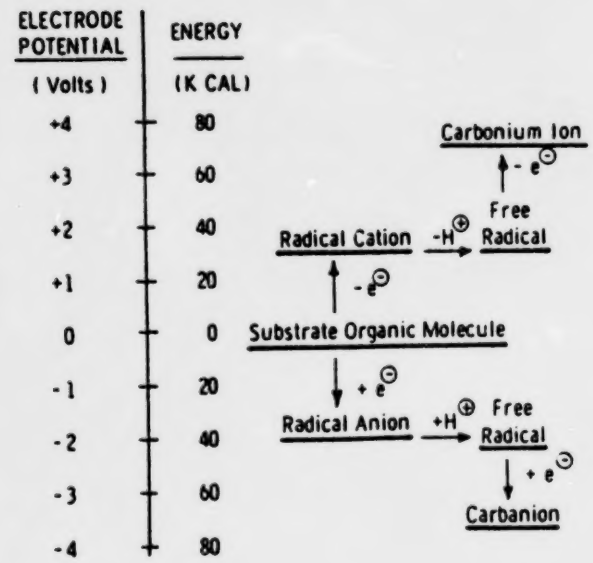


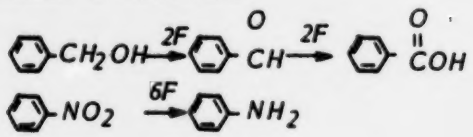

FIGURE 3A

ENERGY VS. ELECTRODE POTENTIAL:
OXIDATION LEVEL OF REACTION INTERMEDITES /3/

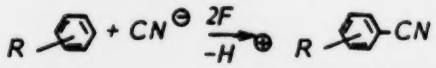
*Halogenation:* $2X^- \longrightarrow X_2 + 2e$

*Generation of acid (at anode) or base (at cathode)*

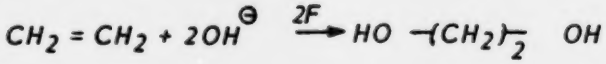
*Group Oxidation or Reduction*



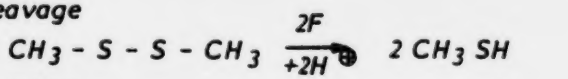
*Substitution*



*Addition*



*Cleavage*



*Coupling*

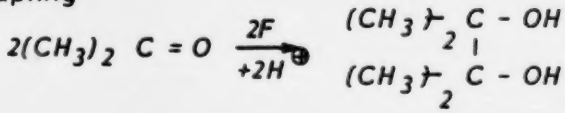


FIGURE 4A

ELECTROORGANIC REACTION TYPES

TABLE 1A

COMMERCIAL AND PROMISING PILOT PLANT ELECTROORGANIC PROCESSES: /5/

C - commercial
P - pilot-scale
(P) - possibly commercial
CE - current efficiency

REDUCTIONS

| Product | Starting Material | Company | Description |
|---|---|---|---|
| adiponitrile | acrylonitrile | 1. Monsanto<br>2. Asahi | C; $2 \times 10^8$ kg/y; Pb cathode<br>C; $2 \times 10^7$ kg/y; Pb cathode |
| o-aminobenzyl alcohol | anthranilic acid | BASF | (P) |
| 1-amino-4-methoxynaphthalene | 1-nitronaphthalene | BASF | (P) |
| p-aminophenol | nitrobenzene | (Japan)<br>Holliday | C; Cu, Hg cathodes<br>C |
| p-anisidine | nitrobenzene | BASF | (P) |
| p-carbomethoxybenzyl alcohol | dimethylterephthalate | Hoechst | P |
| 2,4-diaminophenol | m-dinitrobenzene | (India) | P; Hg cathode |
| 1,4-dihydronaphthalene | naphthalene | Hoechst | P |
| 1,4-dihydronaphthyl ethers | naphthyl ethers | Hoechst | P |
| dihydrophthalic acid | phthalic acid | BASF | C?; Pb cathode |
| hexahydrocarbazole | tetrahydrocarbazole | BASF | C |
| metanilic acid | m-nitrobenzenesulfonic acid | BASF | (P); Pb cathode |
| (corresponding pinacol | p-hydroxypropiophenone | Sorapec (France) | P |
| piperidine | pyridine | Robinson Bros. (UK) | C; $1.2 \times 10^5$ kg/y; Pb cathode |
| salicylaldehyde | salicylic acid | (USSR) | C? |
| succinic acid | maleic acid | (India) | C; $6 \times 10^4$ kg/y |

OXIDATIONS

| | | | |
|---|---|---|---|
| acetylene dicarboxylic acid | butynediol | BASF | (P); $PbO_2$ anode; 75% C.E. |
| amino acids | amides | Hoechst | P; methoxylation reactions - 1/2 kg per day |
| anisaldehyde | p-methoxytoluene | 1. (Sweden)<br>2. Oxy? | P; $PbO_2$ anode<br>C; redox reagent; formerly at "Udylite" |
| anthraquinone | anthracene | Holliday | C; small scale, $PbO_2$ anode with $Cr^{+6}$;<br>(Diamond Shamrock also developing a process?) |
| 2,5-dimethoxydihydrofuran | furan | BASF | C; carbon anode |
| dimethylthiuram disulfide | dimethyldithiocarbamate | DuPont | P; Pt anode |
| fluorinated and perfluorinated organics | carboxylic acids hydrocarbons alkyl-sulfonyl compounds | 1. 3M<br>2. Dai Nippon (Japan) | C; Ni anode<br>C; Ni anode |
| gluconic acid | glucose | (India) | C; $3 \times 10^3$ kg/y |
| hydroquinone or quinone | benzene or phenol | 1. Stavely<br>2. Carus<br>3. Eastman | P; appears very promising; $PbO_2$ anode<br>P?; problems with electrode fouling<br>C?; formerly Union Carbide process |
| isobutyric acid | isobutanol | (USSR) | P; $PbO_2$ anode |
| 2-methyl-1-naphthyl acetate | 2-methylnaphthalene | BASF | (P); carbon anode |
| p-nitrobenzoic acid | p-nitrotoluene | (India) | (P); $PbO_2$ anode; $Cr^{+6}$ |
| perfluoropropylene oxide | perfluoropropylene | Hoechst | P; 20T/y; $PbO_2$ anode |
| propiolic acid | propargyl alcohol | BASF | (P) |
| sebacic acid diester | adipic acid ester | (USSR) | C?; Pt/Ti |
| tetradecanedioic acid | monomethyl azelate salt | Soda Aromatic Co (Japan) | C |

*Adipontrile (Monsanto)*

$$2\,CH_2 = CHCN \xrightarrow{2F} N \equiv C + CH_2)_4 - C \equiv N$$

*Tetraethyl Lead (Nalco)*

$$Pb + 4(C_2H_5)\,MgCl \xrightarrow{4F} Pb(C_2H_5)_4 + 4\,MgCl^{\oplus}$$

**FIGURE 5A**
**CURRENT COMMERICAL PROCESSES**

- Constructors John Brown (England) are developing a process for para-amino-phenol from nitrobenzene.

- In Europe, pilot scale synthesis of benzoquinone, sebacic and dihydrophtalic acids is underway.

5. Economic Aspects

5.1 Operating Cost

Although electricity is an expensive form of energy, it can be used very efficiently in organic electrosynthesis. Moreover the cost of electrical power to industry is not expected to increase as much as gas or oil. The simplicity of electroorganic processes means that less maintenance is required and that a higher degree of automation can be achieved which could result in reduced manpower requirements. Thus, while power costs are always significant, they are not considered the dominating factors in electroorganic processes.

5.2 Investment

Typical investment costs of electro-synthetic processes are given in Table 4A. In Figure 6A a plot of electroorganic process investment per annum in comparison with a wide variety of conventional processes is shown/1.3/. These estimates are normalized to a common basis (MW-100, Faraday-2, current yield 70%, the cost figures are in 1974$). As the preliminary estimates indicate, both operating and process investment costs for many electroorganic processes are comparable with conventional processes.

With the development of new electroorganic reactor technology, these investment costs are likely to be lowered even more. Non-electrolytic process investment will probably shift upward relative to electrolytic processes in the future owing to the need for pollution control.

Because of the potential energy merits, economic competitiveness, reduced pollution, and increased load demand that could result from the commercial application of this technology, the development of electroorganic processes by the Chemical Research Department is recommended.

6. Needs and Opportunities

There are challenging opportunities available in electroorganic processing for developing new reactions, synthesizing new products, improving cell design and converting present energy intensive chemical processes to electrochemical analogues.

Some of the areas requiring further development in electroorganic processing include:

- Electrode specific reactions of organic compounds;

- Mechanistic electrochemistry;

- Electrode materials;

  - Conductive media;

TABLE 4A

TYPICAL INVESTMENT COSTS (BASF)

(At 10,000 T/Year Level)

| | | |
|---|---|---|
| A. | Plant, electrochemical section | 30 to 40% |
| | (cell itself: 2% if undivided<br>10% if with membrane) | |
| *B. | Plant, product/electrolyte separation | 50% |
| C. | Energy (electrolysis, etc) | 15 to 25% |
| | Total | 100% |

---

* Since most of the costs are here, the simplification of product isolation has the most important effects. (Example chloralkali - separation of salts from caustic represents about 20% of plant: Use of a membrane cell solves the problem.)

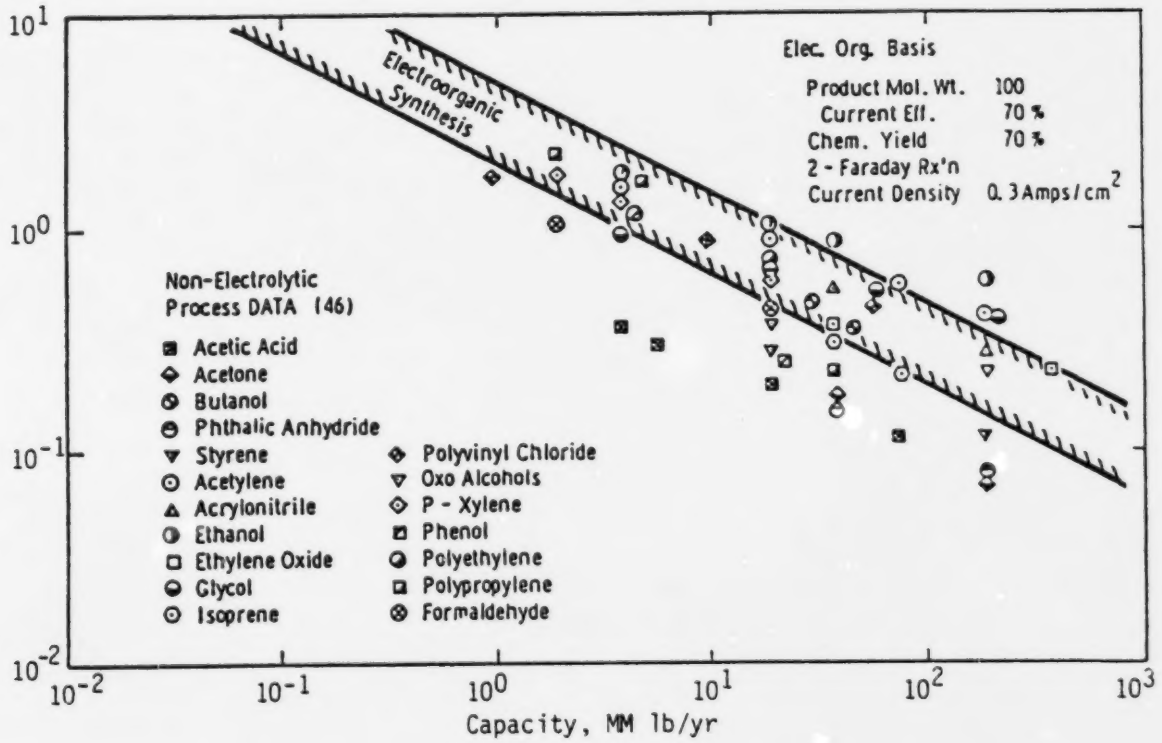



FIGURE 6A

INVESTMENT, ELECTROORGANIC VS CONVENTIONAL PROCESSES

  - Role of adsorption;
  - Tailor made electrodes, high surface area electrodes;
  - Scale up/cell design;

- Environmental aspects;

  - Pollution control;
  - Monitoring devices;

- Electroregenerative processes;

- Bioelectrochemistry.

7. R&D Program for 1985 to 1988

The objective of the program is to develop electrochemical (organic and inorganic) processes capable of producing chemicals of commercial potential in Ontario.

Development of Selected Electroorganic Synthetic Processes

This program will be carried out in two steps:

(a) Literature Review

A literature study is in progress to identify chemicals that could be economically produced using electrochemical methods. Emerging electrochemical technologies will be reviewed to identify larger scale processes with potential for commercialization in the 5 to 20 year time frame.

The project is cofunded by Ontario Hydro and CEA. Dr. N. Weinberg of Electrosynthesis Co, Buffalo is coinvestigator in the project.

(b) Bench Scale Development of Processes for the Electrochemical Production of Organic Chemicals

Processes selected in Phase I of the program will be developed on the bench and later on a pilot scale. An electrochemical cell will be designed, the technical feasibility of the selected system will be demonstrated, and process parameters will be optimized for maximum product yield. Economic feasibility of the process will be assessed and recommendations for scaling up will be made.

The schedule and estimated cost of the five-year program are given in Table 5A.

8. Summary

- Electrochemical, particularly electroorganic synthesis offers opportunities for performing many reactions at a controlled rate and greater product selectivity at higher efficiency than conventional means.

- There are a few successful examples of commercial applications of electroorganic synthesis. Many organic reaction types were identified which could be efficiently conducted by electrochemical means.

- Operating and capital costs of electroorganic synthesis is often lower than conventional processes because of the efficient use of electricity and the higher degree of automation. Manpower requirements are also low.

- There are challenging opportunities in electroorganic processing for developing new reactions, synthesizing new products and converting present energy intensive chemical processes to electrochemical analogues.

- Since the benefits to Ontario Hydro through increased electricity demand could be very significant, the development of such processes by the Chemical Research Department is proposed.

- The proposed five-year plan involves the development and demonstration of the technical feasibility of selected electroorganic and processes capable of producing chemicals with market potential in Ontario.

- In 1985, only one professional manyear is required to conduct the literature study and plan the experimental program. Manpower requirements and costs are expected to increase to about two professionals and two technicians between 1986-1989, with the initiation of the experimental program. Labour and material costs during this period are estimated to be about $330 x 1,000 (1985).

TABLE 5A

ELECTROCHEMICAL SYNTHESIS R&D PROGRAM
SCHEDULE AND COST

| Work Area/Program | Objectives | 1985 | 1986 | 1987 | 1988 | 1989 |
|---|---|---|---|---|---|---|
| Development of selected electroorganic synthetic process | To develop electrosynthetic processes capable of producing organic chemicals with commercial potential | | | | | |
| 1. Literature review | To review the literature and to select chemicals that could be favourably produced by electrochemical means | | | | | |
| 2. Bench scale development and demonstration of selected processes for producing organic chemicals | To develop selected processes on the bench scale and to establish their technical and economic feasibility | | | | | |
| | | Prof Tech | Prof Tech | Prof Tech | Prof Tech | Prof Tech |
| Manpower requirements manmonths/year | | 12 | 20 24 | 22 24 | 24 24 | 22 24 |
| Total cost in $x1000 (1985) (labour, M&E, overhead) | | 90 | 320 | 330 | 330 | 330 |

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# APPENDIX B

# SECONDARY BATTERIES

M.S. Mozes

## ABSTRACT

The potential benefits of high performance rechargeable batteries for the conservation of valuable resources and the environment, and their impact on the electric vehicle market and utility industry is discussed. The technical and economic requirements for EVs and utility applications are established. The development of conducting polymer batteries that have desirable characteristics for both applications is proposed. Objectives of the research program are established and the status of development to date and a five-year research plan, its schedule and cost are given.

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APPENDIX B

SECONDARY BATTERIES

1. Introduction

Electricity could replace a significant portion of the large quantities of oil consumed by the transportation sector, which is largely dependent on imports. Options for electric transportation include electric vehicles (EVs), hybrid vehicles, electric mass transit, electrified railroads and highways. EVs show the largest potential for petroleum substitution; light trucks and cars currently consume about 90% of all petroleum used in transportation.

A secondary battery is an attractive energy storage device and ideally suited for use in EVs. Electric utilities are interested in the development of batteries for EVs since their widespread use could not only significantly increase load demand, but could also enable a more efficient use of existing electric generating capacity through off-peak EV battery recharging that uses economic base-load power. The other potential application of secondary batteries, which is of interest to electric utilities, is for load levelling.

A multitude of electrochemical systems, that are potential candidates for energy storage in transportation and utility applications are being developed in the USA, Japan and Europe, but neither the engineering nor the advanced batteries meet the performance, life and cost standards required for EVs or load-levelling application. Only a few have promise for successful development and penetration before the year 2000.

Battery technologists claim that at the present time the lead-acid battery is the only one commercially available, however, its primary drawbacks are: low energy density, relatively poor cycle life, high weight and cost per kWh.

Some of the electrochemical systems most widely studied are given in Table 1B. Table 2B lists the battery systems that appear to be the most promising for transportation applications/1/, but further development of existing or novel battery systems is necessary to meet higher performance, life and cost standards before they can penetrate the EVs and utility market place.

Since the potential benefits to OH and to Ontario from such a market penetration are great, a battery research program aimed at developing a high performance battery system suitable for EV and utility applications was initiated.

2. Batteries for EV Application

There are many advantages of electric vehicles compared to conventional cars such as: relatively low operating and maintenance cost, low pollution potential and efficient use of available energy resources. Some of the disadvantages include: low vehicle range with available and with most projected advanced batteries and long time required for recharging/3/.

Today EVs cannot compete in the market place with conventional combustion engines which have high performance levels, unlimited range, relatively low cost and an extensive infrastructure to support their distribution and operation.

TABLE 1B

Candidate Battery Systems/2/

Aluminum/air (metal fuel cell)
Calcium/copper fluoride
Calcium/air (metal fuel cell)
Calcium/sulfur
Fuel cells (hydrocarbon or organic fuel)
Iron/air (metal fuel cell)
Iron/air (rechargeable)
Iron/oxygen
Lead/acid
Lithium/air (metal fuel cell)
Lithium/chlorine
Lithium/copper-sulfide
Lithium/iron-sulfide
Lithium/nickel-sulfide
Lithium/selenium
Lithium/titanium-disulfide
Manganese/lead
Manganese/zinc
Nickel/cadmium
Nickel/hydrogen
Nickel/iron
Nickel/zinc
Redox systems
Silver/cadmium
Silver/hydrogen
Silver/zinc
Sodium/air (metal fuel cell)
Sodium/metal chloride
Sodium/sulfur (ceramic)
Sodium/sulfur (glass)
Zinc/air (metal fuel cell)
Zinc/air (rechargeable)
Zinc/bromine
Zinc/chlorine
Zinc/oxygen

TABLE 2B

Promising Electrochemical Systems for Transportation End Use

| Development | Electrochemical System | Electrical Performance | Required Work |
|---|---|---|---|
| | Ni/Zn | Good | Improve cycle life and reduce cost. |
| Engineering | Pb/acid | Marginal | Improve cycle life and specific energy. |
| | Ni/Fe | Marginal | Reduce cost and sensitivity to temperature. |
| | Zn/Cl | Fair | Reduce volume: demonstrate ruggedness and safety. |
| Advanced | Li-Al/FeS | Good | Improve cycle life and reduce cost. |
| | Na/S (ceramic electrolyte) | Good | Improve cycle life, reduce cost, and demonstrate |
| | Polymer | Good | At an early stage of development. |

Commercialization of EVs will require further improvement of present battery and other related technologies.

The technology requirements for EV application include:

- high specific power (Watts/lb);
- high specific energy (Watts-hr/lb);
- long life;
- low maintenance need;
- long activated stand capacity with low self-discharge or degeneration;
- long cycle life;
- rapid rechargeability;
- small size;
- safety during accidents.

In Figure 1B the operating characteristics of some batteries in terms of specific energy and specific power are presented/4/.

One very important characteristic of the battery systems is evident from this figure: the curves - specific power vs specific energy - slope up and to the left, ie, less energy is available at increased power levels. This is due to the internal battery resistance and various kinds of polarization that constitute irreversible energy losses.

The figure also indicates that discharge times at high power are quite low. For example, a Ni/Cd battery may be operated at a very attractive 300 W/h but only for 1 min. Batteries with these characteristics are useless for the sustained operation required in an EV. Batteries with much better performance characteristics will have to be developed.

## 3. Batteries for Utility Systems

The principal application of batteries in utility systems is for load levelling: the batteries store cheap base load energy during an off-peak period and are discharged during periods of high demand.

In addition to storing energy for load levelling and peak shaving, batteries can provide spinning reserve - instantaneous emergency power in the event of a sudden power plant outage.

The unique capability of batteries to respond to a momentary fluctuation in load demand is also important in system regulation. Some of the potential benefits of this application are:/4/

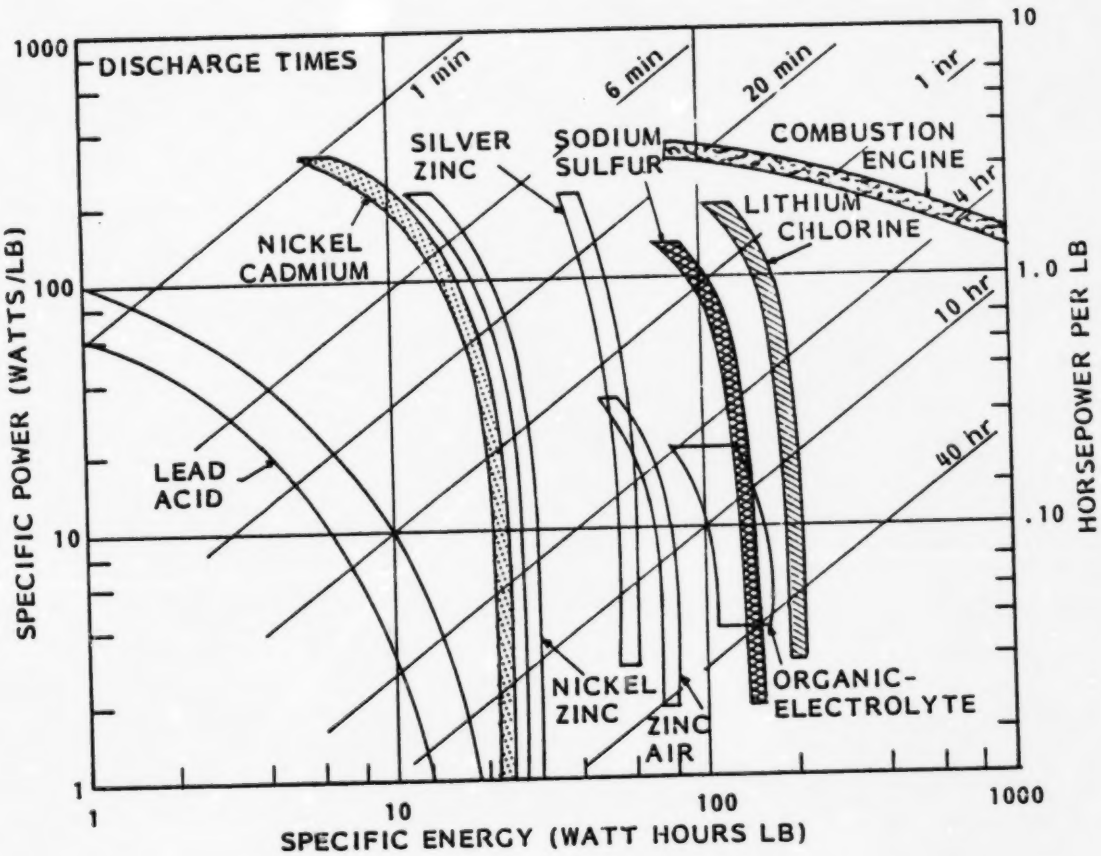



FIGURE 1B

SPECIFIC POWER VERSUS SPECIFIC ENERGY
FOR BATTERIES WITH LINES OF CONSTANT DISCHARGE TIME

- conservation and efficient use of available energy resources;
- lower cost of electric energy (savings in fuel cost, improved utilization in capital equipment);
- conservation of the environment;
- modulability and low capital cost;
- savings in power transmission;
- short lead time for construction;
- operable over widely varying load;
- reliability in power emergency (unique capability to respond to momentary fluctuations in load demand).

It was estimated/3/ that future competitive storage systems in the US could penetrate the utility market to about 15% of peak load demand and supply about 5% of the total electric energy. Similar market penetration could be expected in Ontario and such a market could also open up high technology related manufacturing opportunities in Ontario.

4. Advanced Battery Systems

Recognizing the potential benefits and needs of energy storage batteries for the applications described, a battery R&D program was initiated in 1981 in the Chemical Research Department.

It was realized that any successful advanced battery system would have to meet the technical and economic requirements of the batteries for the specific applications. The tentative battery requirements for applications in electric vehicle propulsion and utility load levelling are stringent as shown in Table 3B/3/.

Some experts feel that the best battery system may come from exploratory battery systems/2/. The future of battery technology may depend on the successful development of novel batteries. Thus it was decided to direct the Chemical Research Department's Battery Research Program toward this end. Obviously the risk involved is relatively high since major technical advance will be required before technical/economic success can be achieved.

5. Risk Evaluation

A risk/reward relationship was developed for the most promising battery system by an "Electrochemical Panel"/2/. The assessment of risk was based on the evaluation of the number and difficulty of technical barriers to be overcome for each battery system. Table 4B summarizes these barriers. The major obstacle for most batteries include: specific energy, lifetime cost, and suitable materials for cell components. Difficulties in finding such materials has resulted in problems with separators, positive electrode current collectors and leads. Thus corrosion, electrode degradation and impurities are the major problems of many of the advanced systems.

TABLE 3B

Battery Requirements for Utility Load-Levelling and Electric Vehicle Applications

| | Utility Load-Levelling | Electric Vehicle |
|---|---|---|
| Duty Cycle | 10 h discharge/daily<br>5-7 h charge/daily | 2-4 h discharge<br>1-5 h charge |
| Energy Efficiency | >70% | >50% |
| Cycle Life | >2,500 cycles<br>(10 years) | >1,000 cycles<br>(3-10 years) |
| Cost | Low | Low |
| Environmental Impact | Minimal | Minimal |

TABLE 4B

TECHNICAL BARRIER SUMMARY

| Technical Barrier[a] | Battery | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pb/Acid | Ni/Fe | Ni/Zn | $Zn/Cl_2$ | $Li\text{-}Al/FeS_x$ | Na/S (Ceramic) | Na/S (Glass) | Polymer |
| Specific energy | X | | | | X | X | X | X |
| Volumetric energy Density | | | | X | | | X | |
| Power capability | | | | | | | | |
| Cost | | X | X | X | X | X | X | |
| Lifetime | X | | X | X | X | X | X | X |
| Materials corrosion | | | | | X | X | X | X |
| Cell Scale-up | | | | | | | X | X |
| Safety | | | | X | | X | X | X |
| Separator | | | X | | X | X | X | |
| Battery development[b] | | | | | XX | XX | XX | XX |
| System complexity and/or flexibility | | | | X | | | | |
| Total barriers | 2 | 1 | 3 | 5 | 7 | 8 | 10 | 7 |
| Relative difficulty factor | 3.0 | 2.5 | 5.5 | 8.0 | 10.0 | 11.0 | 14.0 | 10.0 |

[a]Technical barriers not expected to involve serious development difficulty are not included.

[b]Absence of significant battery development and testing is arbitrarily considered to represent two barriers.

The general conclusion from the risk evaluation (Figure 2B) is that the overall probability of successful technical/economic development of any single system is less than 50% except for the low performance Pb/acid and Ni/Fe batteries. However taken together, the overall probability that at least one system will be successfully developed appears to be at least 75%.

The plot in Figure 2B indicates a rough proportionality between the difficulty of development and the desirability (favourable characteristics) of the resulting battery. Based on preliminary work conducted at the electrochemistry laboratory of the Chemical Research Department, polymer batteries were rated to have very desirable characteristics for transportation and utility application with relatively high development risk.

Because of the potential that successfully developed polymer batteries offer for both EV and utility applications, a research program was initiated to study and develop conducting polymer batteries.

## 6. Conducting Polymers for Use in Batteries

### 6.1 Nature of Conducting Polymers

There is a growing world-wide interest in conducting polymers, ie, organic polymers that can be rendered highly conductive on doping/6/. Many applications can be envisioned for these electroactive materials which possess the high conductivity of metals, and the light-weight, flexibility, processability and low cost common to plastics.

Some potential applications for these materials include:

- batteries;
- p-n junctions;
- photoconductors;
- electrocatalysis;
- protective coatings;
- mass data storage;
- microwave absorbers.

Some of the base polymers can be synthesized by a one-step electrochemical process from a variety of monomers with conjugated double bonds.

These polymers become highly conductive on either vapour or liquid phase doping with strong electron acceptors or donors. They can also be doped (oxidized or reduced) electrochemically in a reversible manner in non-aqueous solvents under an inert atmosphere. This property is ideal for energy storage application.

Because of its technological potential, polymer battery development work is being conducted all over the world:

Japan - Toyota Central R&D Lab;

France - University of Rennes;

USA - University of Pennsylvania
- Allied Corporation;

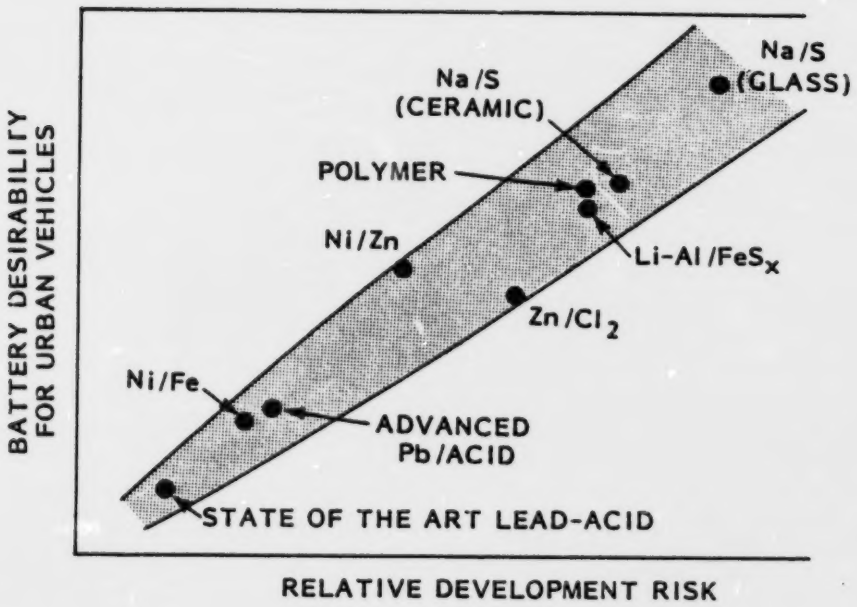



FIGURE 2B

RISK/REWARD RELATIONSHIP
FOR ADVANCED BATTERIES

- Johnson Controls;
- Chevron Research;
- Rohm and Haas;
- Naval Research Lab;
- Sandia National Lab.

Preliminary research results indicate that electrodes fabricated from conducting polymers are ideally suited for use in lightweight batteries because of:

- high electronic conductivity;
- high charge and current capacity;
- stability in many electrolytes;
- structural integrity; and
- long cycle life.

Polyacetylene. Among the known conducting polymers, polyacetylene is the most widely investigated. It has been the first polymer to display high conductivity upon doping. The relatively simple structure of polyacetylene provides a useful model for theoretical and experimental studies. The charge process of a polyacetylene battery is shown in Figure 3B/7/.

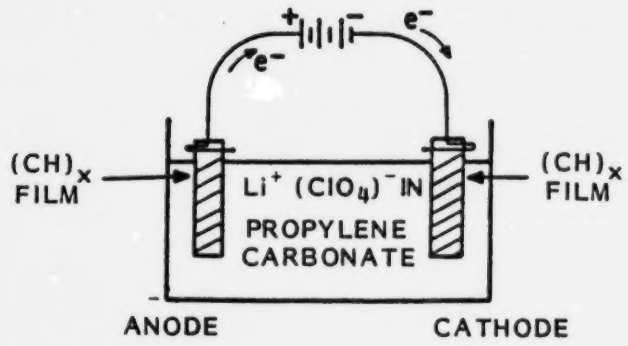
If two strips of polyacetylene (CH)x film are placed in a solution of LiC10 in propylene carbonate and are attached to the positive and negative terminals of a dc power source ( 4 v), oxidation of the (CH)x occurs at the anode and reduction at the cathode during the charging operation. In order to balance the charge acquired by polyacetylene films, counter ions from the electrolyte diffuse into the film. The reduced form is very reactive to moisture and oxygen.

Unfortunately, polyacetylene is unstable and becomes brittle after only a few days of exposure to air with a resulting decrease of conductivity. Another problem appears to be low coulombic efficiency during repeated charge/discharge cycles. These problems are attributed to impurities in the electrolyte and the inherently high electrode potential of doped polyacetylene.

Other Conducting Polymers. The electrochemical and physical characteristics of conducting polymers can be modified by substitution of the monomer. A large number of such new polymers are being developed and tested by many leading research laboratories/6-9/. A list of these polymers is given below:

poly (p-phenylene)
poly (p-phenylene vinylene)
poly (p-phenylene sulphide)
polythiophene
polypyrrole
poly (1,6-heptadiene).

Most of these compounds form highly conducting charge-transfer complexes with both n- and p-type dopants/7/. In some cases the conductivity of the polymer should increase more than 14 orders of magnitude in going from the undoped to the highly doped polymer/8/. Varying the concentration of the dopant allows the conductivity to be adjusted within a very broad range.




AT ANODE (+)

$$(CH)_x + xy(ClO_4)^- \rightarrow [(CH)^{+y}(ClO_4)^-_y]_x + xye^-$$

AT CATHODE (-)

$$(CH)_x + xyLi^+ + xye^- \rightarrow [Li^+_y (OH)^{-y}]_x$$

NET REACTION

$$2(CH)_x + xyLi^+(ClO_4)^- \rightarrow [(CH)^{+y}(ClO_4)^-_y]_x + [Li^+_y(CH)^{-y}]_x$$

FIGURE 3B

CHARGE PROCESS OF A POLYACETYLENE BATTERY

The doping effect is explained as follows: A rigid band structure is assumed in which the dopant's function is to transfer electrons onto the polymer chain (electron carriers) or away from the chain (hole carriers). At low dopant levels the carriers created on the chain are expected to be bound in the vicinity of the dopant. However, at sufficiently high dopant concentrations, screening by the contributed carriers will be sufficient to cause the material to undergo an insulator-to-metal transition.

It must be remembered, however, that the field of conducting polymers is at the early stages of development and their full potential has yet to be exploited.

## 7. Polymer Battery Development Program

A research program, initiated in June 1983, is in progress, and its objective is to develop lightweight polymer batteries with high energy and power density and long cycle life suitable for EV and utility applications.

### 7.1 Status of the Program

The program is conducted in two phases. Phase I of the program is nearing completion. This phase involves the development and characterization of new conducting polymers and Phase II is aimed at evaluating polymer batteries using the most promising polymers developed in Phase I.

Phase I: New conducting polymers based on heterocyclic monomers have been developed and characterized. Electrochemical polymerization of selected monomers has been successfully carried out to yield reproducible thin films of polypyrrole, polythiophene and other polymers coded HP021, HP023 and HP024. During investigation of electrochemical charge/discharge characteristics of these materials it was found that these materials appear to be stable and can be p-doped to yield maximum open circuit potential of 4.2V versus Li reference electrode. Doping levels of approximately 20% have been achieved on a micro-electrode, and they have shown good charge/discharge behaviour.

### 7.2 Secondary Battery Research Plan, Schedule and Cost

(a) Polymer Batteries

- based on the studies conducted in 1984, stable conducting polymers with high charge capacity will be selected and used to fabricate electrodes in 1 $cm^2$ single cells and their performance characteristics such as energy and power density, energy efficiency, charge/discharge behaviour, shelf life, and cycle life will be assessed.

- Multiple cell stack using about 10 $cm^2$ electrodes fabricated from the most promising polymers will be designed, constructed and their performance characteristics evaluated.

(b) Other Advanced Batteries

- A critical evaluation of emerging battery technologies through literature surveys and discussions with developers to keep abreast with the advances of the technology will be conducted periodically.

- Performance characteristics (ie, charge/discharge characteristics, cycle life and shelf life) of prototype advanced batteries will be evaluated at the Battery Test Facility to assess their suitability for electric vehicle and energy storage applications in the Canadian environment.

The schedule and cost of the program are given in Table 5B.

8. Summary

- The secondary battery is an attractive energy storage device suitable for EV and utility applications.

- Widespread use of EVs could increase load demand and enable a more efficient use of existing generating capacity through off-peak EV recharging.

- The main application of batteries in utility systems is for load levelling; ie, the batteries store cheap baseload energy during off-peak periods and discharge during periods of high demand.

- Although a large number of batteries are being developed all over the world, neither the engineering nor the advanced batteries developed to date meet the performance, life and cost standards required for these applications.

- Because of the potential market and other benefits that battery technology offers to Ontario Hydro, a five-year research program aimed at developing and evaluating high performance, low cost batteries is proposed.

- The five-year plan involves:

  (a) the laboratory scale (1 $cm^2$ single cell and 10 $cm^2$ multiple cell stack) development and characterization of polymer batteries with high energy and power density and long cycle life;

  (b) keeping abreast of the development of advanced battery technology and evaluating the performance of some promising prototypes of advanced batteries at the Battery Test Facility.

- Manpower requirements and program cost is expected to increase when we plan to test prototypes of advanced batteries at the battery test facility and to fabricate and evaluate the performance of small scale batteries. The program cost is estimated to peak in 1988. (Two professionals and three technicians - $400 x 1000 (1985).)

TABLE 5B

SECONDARY BATTERIES RESEARCH PROGRAM
SCHEDULE AND COST

| Work Area | Objectives | 1985 | 1986 | 1987 | 1988 | 1989 |
|---|---|---|---|---|---|---|
| Polymer batteries | To develop lightweight polymer batteries with high energy and power density and long cycle life.<br>- Performance assessment of a 1 $cm^2$ single cells.<br>- Performance assessment of approx $10^2$ multiple cell stack. | | | | | |
| Other advanced batteries | To keep abreast with the development of advanced battery technology.<br>- State-the-art reviews.<br>- Performance assessment of prototypes of advanced batteries at the Battery Test Facility | | | | | |
| | Manpower Requirements (manmonths) | Prof 18 Tech 12 | Prof 22 Tech 24 | Prof 20 Tech 24 | Prof 22 Tech 36 | Prof 20 Tech 36 |
| | Estimated cost (OM&E) $1000 (1985) | 210 | 320 | 320 | 400 | 400 |

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# APPENDIX C

# FUEL CELLS FOR POWER GENERATION

R.K. Kalia

## ABSTRACT

The potential application of fuel cell power plants (FCPP) to electric utility power systems and Ontario Hydro's interest in this efficient, modular generation option are discussed. The types of fuel cells suitable for utility application are briefly described. A five-year research program aimed at evaluating the development of the various fuel cell technologies and participating in the field testing of prototype FCPP is described. The schedule and cost of the program are also given.

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APPENDIX C

FUEL CELL POWER PLANT

1. Background

The fuel cell is a device in which fuel and oxygen (from air) react electrochemically to produce direct current electricity and water.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{DC current}$$

Since there is no combustion cycle, there are no air emissions from the fuel cell itself. There are also no moving parts to wear out. The fuel cell can be compared to the cell in a conventional lead-acid storage battery. That is, it is comprised of two electrodes and an electrolyte. Phosphoric acid is the electrolyte which will be employed in the first generation of fuel cells planned for commercialization. The fuel cell differs from a storage battery in that as long as the fuel and air are supplied, electricity and water will be produced. Thus, a fuel cell does not need charging to regenerate the reactants as is the case with a storage battery.

Each fuel cell within a fuel cell power plant (FCPP) has an output of about 0.7 volts dc. To increase the voltage to levels necessary for large-scale power generation, individual cells are assembled into multi-cell stacks. In one manufacturer's design, 18 stacks are connected (in series and parallel combinations) to make up the FCPP's power section which provides 11 MW ac net.

The practical integration of FCPPs into conventional electric utility systems requires that they utilize available fuels and produce utility grid compatible ac power. Therefore, a utility FCPP includes a fuel cell power section, a fuel processor and a power conditioner, as shown in Figure 1C. The fuel processor converts the hydrocarbon fuel source (ie, natural gas, light distillate, synthetic natural gas (SNG), coal-derived fuels, methanol, etc), into a hydrogen-rich gas for utilization in the power section. Dispersed fuel cell power plants would most likely operate on liquid or gaseous fuels. Central stations or dispersed power plants integrated with coal-gasifiers would be able to use coal or lignite directly. The power conditioner converts the dc output of the power section to ac power suitable for direct input into the transmission or distribution grid of the utility system.

2. Potential Benefits of FCPPs for Electric Utilities

The fuel cell is a unique and versatile power source in a number of ways. The characteristics of fuel cells suggest that such generators may be able to provide a number of benefits not available from conventional thermal generating equipment. The characteristics of FCPPs and potential benefits for electric utilities are summarized in Table 1C. FCPP is also a versatile power generator with the potential for broad application in the electric utility industry.

Some of the attractive features of FCPPs for power generation are highlighted below:

- Fuel cells are very efficient. Because of direct energy conversion, fuel cells are not limited by Carnot cycle efficiency. Heat rates as low as

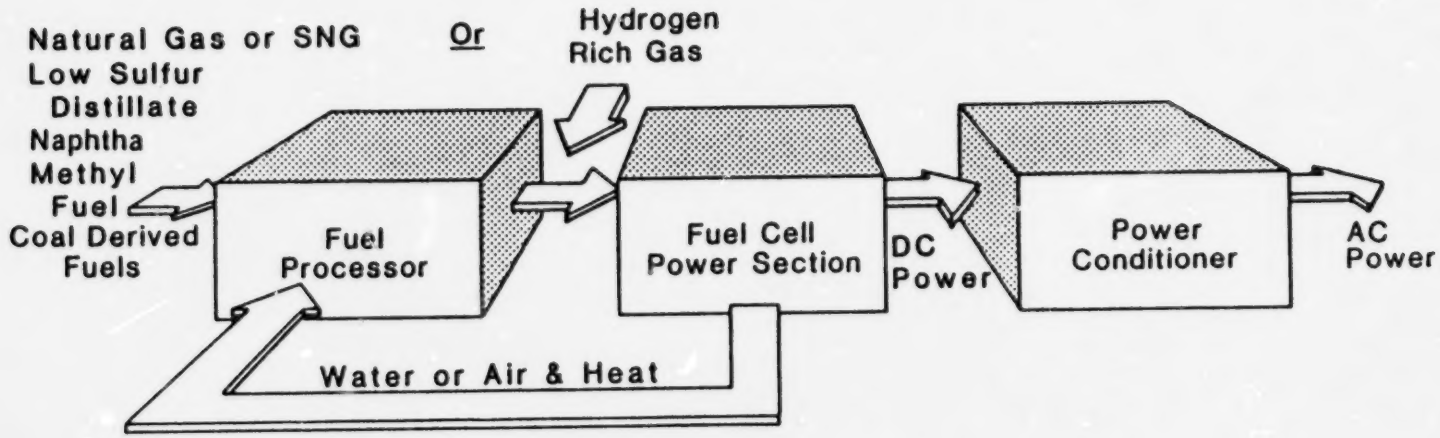


FIGURE 1C

FUEL CELL POWER PLANT

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TABLE 1C

FUEL CELL POWER PLANTS

| Characteristics | Benefits |
|---|---|
| - Modular size<br>- Short lead time | - Minimize financial impact<br>- Better capacity/load match<br>- Enhance planning flexibility |
| - Low emissions/water use<br>- Truck transportable | - Broad siteability |
| - High efficiency -<br>  - 8300 Btu/kWh at 100% F.L.<br>  - 9000 Btu/kWh at 50% F.L. | - Fuel conserving |
| - Unmanned operation | - Minimize operating costs |
| - Dispersed siting | - Decrease transmission line losses<br>- Defer transmission line construction |
| - Waste heat recoverable | - Cogeneration application |
| - Factory manufactured | - High quality control |
| - Multiple fuels<br>  - Distillates, methane, LPG, coal-derived fuels, hydrogen<br>  - Retrofittable | - Use today's fuels today<br>- Switch to coal-derived fuels tomorrow |
| - High availability (85-95%) | - Reduced reserves |
| - Var control | - Less capacitor installations |
| - Load following | - Enhance operational flexibility<br>- Improve system operations<br>- Provide spinning reserve |

7200 kJ/kWh can be projected. Current fuel cell technology provides heat rates of about 9500 kJ/kWh; next generations of fuel cell technologies are expected to deliver heat rates as low as 7400 to 7900 kJ/kWh/1/.

- They are suitable for siting almost anywhere with little environmental impact. This could reduce the need for bulk transmission facilities and sometimes solve difficult transmission corridor problems.

- Due to the modular character of the fuel cells they allow a wide latitude in construction and planning. The fuel cells can be factory produced within 18 months to 2 years lead time. The utility system capacity can be increased in small increments with additional modules thus minimizing capital outlays. This reduces the financial risks associated with long lead times of large scale generation options.

- With fast load response (1 MW/sec)/2/ and high reliability they could operate unattended. These and other characteristics provide the operator with voltage support and reduce the need for spinning reserve/2/.

- In a large fuel cell system the waste heat is a valuable by-product that could be used for heating, air conditioning and process needs.

In a recent study by EPRI/3/ nine utility power supply situations favourable to fuel cell applications were defined.

These include:

- a requirement for intermediate/peaking capacity;

- capacity planning uncertainties;

- narrow reserve margins;

- natural gas availability;

- availability of an unconventional fuel supply;

- high-cost power alternatives;

- cogeneration possibilities;

- environmental constraints;

- isolation (isolated systems).

Some of these situations exist in Ontario Hydro, thus there is a potential for fuel cell system application at Hydro. Because of their distinct siting advantages and environmental compatability, the immediate application in Ontario Hydro appears to be in peaking and load following dispersed generation. The dispersed generators will reduce costs and losses and will permit a rapid low cost capacity expansion. Because fuel cell efficiency is practically independent of size, another immediate application may be high efficiency base load small power plants/1/.

In the 10-20 year time frame, fuel cells can also be visualized for industrial cogeneration applications where electricity is generated on site to satisfy electrical demand and reject heat may be used to satisfy thermal demand. Overall energy efficiencies of 60-80% can be obtained depending on the ratio of thermal to electric demand and other design parameters/1/. Market analysis by Westinghouse/3/ has indicated that the utility ownership of even smaller size power plants (approx 120 kW) for on-site, integrated energy systems for apartment complexes and commercial buildings may be beneficial because of financial, regulatory and reliability considerations.

## 3. Status of Fuel Cell Power Plant Development

Although the fuel cell was first invented in 1839, it remained little more than a curiosity until the 1960s when hydrogen and oxygen fuel cells were developed for use in the US space program. The successful employment of fuel cells in the space program encouraged efforts to develop fuel cells for utility power generation. These efforts led to the development of a 4.5 MW demonstration FCPP located in New York City with Consolidated Edison Company as the host utility. This demonstration FCPP became operational in 1982 and operates in parallel with the utility's distribution system. A second 4.5 MW demonstration plant is in operation at the Tokyo Electric Power Co.

Several organizations in the US and Japan are vigorously involved in technology development, application studies, system design, market analysis and field testing. The US Department of Energy has established a fuel cell project office to coordinate its fuel cell programs. EPRI and the Gas Research Institute have been funding fuel cell development. A fuel cell users group (FCUG), consisting of approximately 40 electric utilities formed in 1980, has been aiding the transfer of fuel cell technology from demonstration stage to utility service. The members are kept aware of the current status of the fuel cell technology at regular intervals.

Other major demonstration activities in progress include:

- About four dozen 40 kW FCPP pilot units are planned to be evaluated at a number of organizations. Two of these units have been bought by NRC and IREQ.

- Westinghouse Electric Company is planning to build a 7.5 MW unit for demonstration at a host utility.

This level of activity in different sectors gives an excellent promise for the fuel cell power plants to become a reality.

## 4. Fuel Cell Types for Utility Applications

Phosphoric Acid Fuel Cell (PAFC) Technology PAFC technology is at the most advanced stage of development and all field testing activity is focussed on this technology. Output capacities presently range from the low kW to the low MW range. United Technology's (UTC) water cooled PAFC technology is generally referred to as the "first generation" technology. Other organizations conducting notable work on PAFC technology include: Energy Research Corporation (ERC), Institute of Gas Technology (IGT), Westinghouse, Toshiba and Sanyo. These fuel cells can be utilized in a wide variety of applications including vehicular, portable or remote power; central station and dispersed utility

power; on-site integrated energy systems; and industrial cogeneration of heat and electricity.

PAFC uses 85-100% phosphoric acid as the electrolyte and platinum based electrocatalysts. Current Pt loading is about 5 g/kW/4/ and forms about 10% of the cost of a large power plant. Pt loadings of 3 g/kW have been found satisfactory in smaller units and further reductions are possible. The cell runs on air and hydrogen produced from coal and various liquid and gaseous fuels. CO in the hydrogen fuel (made by reformation of fossil fuels) acts to poison the Pt catalyst. CO content of the reformed fuel must be reduced by passing it through a water gas shift converter. The increase in temperature improves the CO tolerance of the fuel cell but the long term performance of the fuel cell starts degrading due to sintering of the catalyst crystallites.

Research efforts are underway at UTC and other organizations to lower costs, and improve life, energy efficiency and power density by operating at higher temperatures (up to 215°C) and pressures (up to 300 kPa), reducing platinum loading and finding alternate catalysts and electrolytes.

It is expected that advanced versions of PAFC technology will cost 600-800 dollars/kW, in large power plants. Life expectancy of these cells is expected to be about 30 years.

Molten Carbonate Fuel Cell (MCFC) Technology Molten carbonate cells are the developmental fuel cells approaching the pilot plant stage. UTC, ERC (in collaboration with Westinghouse) and IGT (in collaboration with General Electric) are developing this technology, generally referred to as the 'second generation' fuel cells. This technology is considered most suitable for large utility and industrial cogenerating installations of multimegawatt size.

MCFC operates at 480 - 760°C with molten lithium/potassium carbonate mixture as the electrolyte. No precious metal electrocatalysts are required. They use impure hydrogen and ambient air. They are considered suitable to operate in conjunction with coal gasification plants. They can be operated with reformed natural gas like PAFC but the fuel reformer is simpler.

Recent work at ERC is aimed at natural gas fuelled MCFC systems where reformation of natural gas occurs in situ thus eliminating the need for an external reformer.

MCFC has the potential for high efficiency (52% as compared with about 40% of PAFC) and it yields high quality waste heat.

Because of the severe conditions employed, material design and selection problems are rather challenging. Some of the problems have been identified as: evaporation of the electrolyte, sintering of the anode and instability of the cathode/5/. Another key requirement is the recycling of CO from the anode where it is produced; to the cathode where it is consumed. Present development effort in MCFC technology is focussed on these and other manufacturing problems.

As the technology stands, single cells as large as 1500 $cm^2$ have been tested for 5000 hours. A small laboratory cell has been tested for more than five years. A limited number of about 1000-$cm^2$ 20-cell stacks have been tested for short

periods at UTC and additional testing is planned. ERC expects to build a ten cell stack with 1500 $cm^2$ electrodes by the end of next year/4/.

In a megawatt size power plant the cost of MCFC technology is estimated to be about $1,300/kW of which $300 is the cost of the fuel cell itself/5/. The material cost of the fuel cell is only $60/kW/4/.

Solid Oxide Fuel Cell (SOFC) Technology SOFCs operate at extremely high temperatures of about 1000°C. Still being developed at laboratory scale, they are energetically very efficient and have the potential of being the heart of a multimegawatt utility or industrial cogenerating installation. Efficiencies of up to 54% have been demonstrated.

Oxide ion conducting yttria or calcia stabilized zirconia ($ZrO_2$) serves as the electrolyte. Non-noble metal electrodes are used. Oxide ions formed at the cathode are transported through the zirconia wafer electrolyte to the anode where $H_2$ and CO are formed. The operation of the cell is essentially non-catalytic and the cell can tolerate high concentrations of CO. Medium BTU coal gas generators are considered suitable fuel processors. Running on natural gas, internal reformation seems possible/5/ so that the fuel reformer unit may not be needed.

Because of the extreme temperatures employed by SOFCs, most problems that have been identified are material in nature such as: lack of suitable interconnection material compatible with electrolyte, electrode and other cell components, carbon deposition at anode, cracking of cells due to thermal expansion mismatching and change in the nature of electrodes due to sintering. Completion of material developmental tasks is expected to be many years away.

The most notable work on SOFC has been conducted at Westinghouse where a battery of 20 cells with an electrode area of 2 $cm^2$/cell has been tested. At present Westinghouse is conducting a major program on the development of SOFC technology. Considerable advancements are being made also in a closely related technology -- vapour phase electrolysis of water using oxide ion conducting electrolytes/6/. Practically all aspects of this technology will be applicable to SOFCs however it is too early to make any cost estimates of this technology.

## 5. Ontario Hydro's Interest in Fuel Cell Power Plants

It is reasonable to expect that PAFC power plants will be commercially available during the next 10-20 years, although developers maintain it will happen within the next 10 years. Since MCFC technology will benefit from most of the developments and experience gained in PAFC technology, it is also expected to be commercial during the same time frame.

Provided the cost and performance goals are met, PAFC power plants will offer Ontario Hydro a generation option which is environmentally benign, modular and efficient, and has short construction lead-time. The 5-25 MW plants dispersed throughout the utility network can be used to perform load following duty. They may also be suitable for power generation in remote areas where costs of fuel and power transmission are high. In addition, they may find application with large residential and commercial customers who can utilize the low temperature waste heat for space and water heating.

Around the same time when MCFC power plants are commercially available, they may find application in intermediate and base load generation and industrial cogenerating installations of multimegawatt size. In light of these possible applications of fuel cell technology, it is prudent that OHRD closely monitor developments in these fuel cell technologies.

6. R&D Program

In light of the potential benefits and the possible broad applicability of FCPPs in Ontario Hydro's system, a modest activity is recommended in the Chemical Research Department. The objectives of this program are:

- to monitor the latest development of this fast emerging technology and to assess the economic viability of the most promising fuel cell power generation options;

- to participate in field testing of advanced fuel cell power plant prototypes.

In the process of doing this work we will: (a) acquire and maintain awareness of developments taking place elsewhere and be able to alert others within Ontario Hydro to opportunities; (b) be able to develop and exercise technological leadership within Ontario Hydro, and (c) become an informed buyer in case of adoption of fuel cell generation option by the Corporation.

(a) Technology Reviews and Assessment of the Technical and Economic Viability of the Technology

To keep abreast of the latest development of fuel cell technology, yearly technology review updates will be conducted. Advances will be closely monitored by active participation in the Fuel Cell User's Group and CEA fuel cell programs. Seminars and conferences related to fuel cell development will be attended and technical and economic viability and the applicability of the most promising fuel cells to Ontario Hydro's system will be assessed.

(b) Field Testing of Prototype Fuel Cell Power Plants

Hands-on experience on an FCPP installed at a Canadian utility system could lead to a better utility understanding of factors important to system planning. The purchase of such a unit by OHRD for testing at this stage is perhaps not justified because of high capital costs (1.3 million dollars) and manpower requirements (approximately four manyears). Moreover, the performance data generated during this test program will not be significantly different from that generated by other organizations. It is recommended that arrangements be made so that OHRD personnel can participate in one of the test programs, for example, at NRC or IREQ. Establishment of the Canadian equivalent of the Fuel Cell Users Group could provide another opportunity of sharing the cost with other utilities.

An option to purchase and evaluate an advanced pilot plant FCPP should be kept open until around 1987-88 when they are expected to be available. The program cost and schedule are summarized in Table 2C.

## 7. Summary

- The fuel cell is a unique and versatile power source with the potential for broad application in the electric utility industry (peaking, load following, dispersed generation, etc).

- Provided that cost and performance goals are met, fuel cell power plants could provide an environmentally acceptable, efficient, modular generation option that requires short construction lead time.

- Some of the potential benefits of fuel cell power plants (FCPP) for electric utilities include: better capacity/load match, enhanced planning flexibility, fuel conservation, reduced transmission costs, enhanced operational flexibility, improved system operation, provision of spinning reserves, broad siteability, etc.

- Because of the potential benefits an FCPP could offer to Ontario Hydro, a five- year research program is proposed. The objectives of the program are to monitor the latest development of fuel cell technology, assess the technical and economic viability of the most promising fuel cell options and to participate in the testing of prototypes of advanced fuel cell modules.

- Until 1988, our involvement will be limited to keeping abreast with the development of the technology. In 1988 the testing of an advanced prototype fuel cell module installation of Ontario Hydro's power grid is proposed.

- The estimated labour and material cost in 1988 and 1989 is about $340,000 (two technicians and two professionals) and the cost to purchase an advanced pilot fuel cell module is about $1,000,000 (1985$).

TABLE 2C

FUEL CELL R&D PROGRAM
SCHEDULE AND COST

| Work Area/Program | Objective and Description of Work | 1985 | 1986 | 1987 | 1988 | 1989 |
|---|---|---|---|---|---|---|
| Assessment of fuel cell power generation option in Ontario Hydro | To develop technological leadership in the Corporation and become an informed buyer.<br>- Technological reviews, technical and economic evaluation of promising systems. | | ——— | | ——— | |
| Field testing of advanced FCPP | Advanced prototype cells will be evaluated. This program will be initiated in 1988. | | | | ——— | ——— |
| | Manpower requirements, manmonths | Prof Tech | Prof Tech<br>4 | Prof Tech | Prof Tech<br>24 24 | Prof Tech<br>24 24 |
| | Estimated cost (Labour+M&E incl overhead) $x1000 (1985) | | 30 | | 180 144<br>340 | 180 144<br>340 |
| | Major Capital Equipment $x1000 (1985) (Pilot scale fuel cell module) | | | | 1000 | |

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